ORBITAL EXPRESS
AUTONOMOUS RENDEZVOUS AND CAPTURE FLIGHT OPERATIONS

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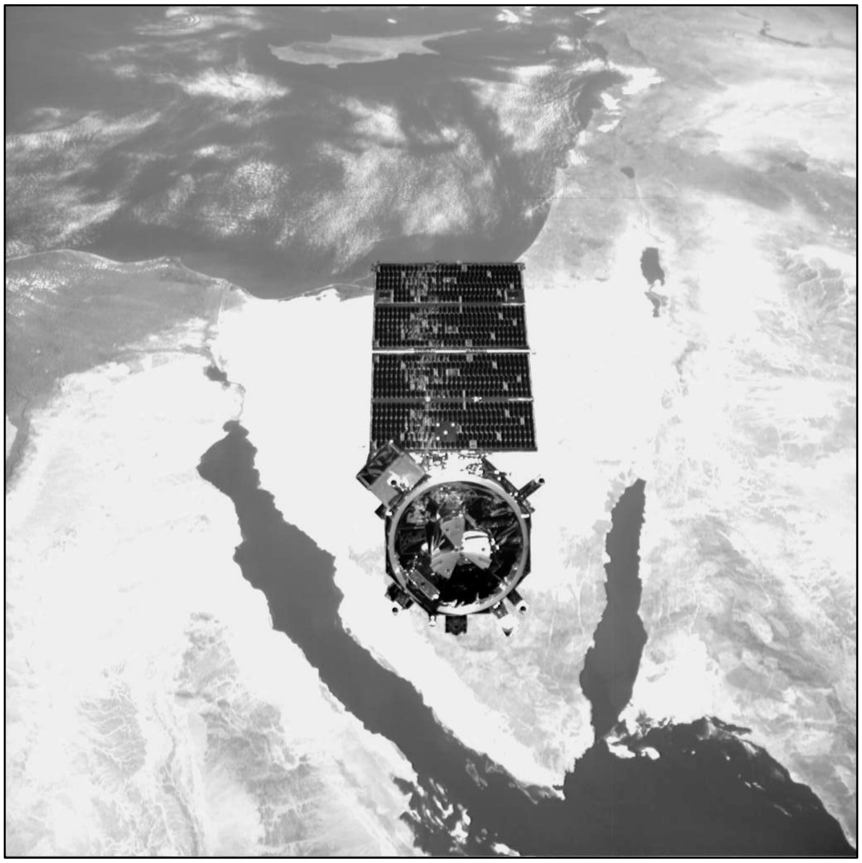

The Orbital Express flight demonstration program was established by the Defense Advanced Research Projects Agency (DARPA) to develop and validate key technologies required for cost-effective servicing of next-generation satellites. A contractor team led by Boeing Advanced Systems built two spacecraft; launched in a mated configuration atop an Atlas V rocket from Cape Canaveral, Florida, on 8 March 2007. The mission concluded with the decommissioning of both spacecraft thousands of kilometers apart on 22 July 2007. The low earth orbit test flight met 100% of its mission objectives, while achieving a number of firsts in space operations. During mated operations, repeated demonstrations were made of autonomous propellant transfer between spacecraft. A robotic arm autonomously transferred a supplemental battery and backup computer. During six unmated exercises, new ground was tread in autonomous rendezvous and proximity operations. Two types of autonomous capture capped off the first five exercises. The majority of autonomous rendezvous and capture (AR&C) operations proceeded smoothly. Some did not and required software updates to overcome differences between ground and space environments. Under all circumstances, the ground team performed well and was treated to a tremendous learning experience. This paper highlights key events and lessons learned during each AR&C exercise. While it touches on aspects of guidance, navigation, and control; emphasis is placed on the trajectories and operations, themselves.

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BACKGROUND

The Orbital Express (OE) program was managed by the Defense Advanced Research Projects Agency (DARPA), with supplemental funding by the National Aeronautics and Space Administration (NASA), and Boeing Advanced Systems, under Integrated Defense Systems.

The purpose of the OE program was to mitigate multiple technical risks associated with servicing a proposed new breed of government and commercial satellites. Today's satellites are disposable, given that failure of critical components, or depletion of onboard fuel, turns a valuable asset into space debris; eventually to de-orbit, or remain in orbit for a very long time. If, however, satellites are built with modular components and refuelable interfaces, it is conceivable their lives may be extended, and satellite replacement performed on a less frequent timetable. This, of course, requires launch, rendezvous, close approach, and capture by a servicing spacecraft carrying spare parts and fuel. Extending the lives of satellites may lower overall costs and reduce the number of satellites being added to already-crowded orbits.

Until now, the technical difficulty and risk of performing on-orbit rendezvous, capture, component swap-out, and refueling served as a major obstacle to commercial or government investment of engineering and manufacturing funds to build serviceable satellites. To stretch the desirability of satellite servicing further, DARPA declared it best to perform these tasks with limited ground interaction, control, and personnel. Thus, OE was conceived of, funded, and executed to create, implement, and prove the necessary technologies for rendezvous, capture, robotic component replacement, and propellant replenishment, to remove this roadblock. During the OE mission, all of these activities were demonstrated without ground assistance.

INTRODUCTION

OE consisted of two spacecraft that were mated, stacked, and launched onboard a United Launch Alliance Atlas V rocket from Cape Canaveral Air Force Station, Florida, on 8 March 2007. OE and four secondary payloads made up the Air Force Research Laboratory (AFRL) Space Test Program 1 (STP-1).

Boeing served as OE prime contractor, and designed and manufactured the chaser spacecraft, *Autonomous Space Transport Robotic Operations (ASTRO)*, including the end-to-end guidance, navigation, and control (GN&C) system. Ball Aerospace produced the *Next Generation Servicable Satellite (NextSat)*, which served roles as both a commodities depot and satellite in need of repair. Other subcontractors included

- Northrop Grumman Space Technology – Fluid Transfer and Propulsion Subsystem (FTAPS)
- MacDonald Dettwiler and Associates – Robotic arm
- Starsys Research Corporation – Soft capture mechanism
- Draper Laboratory – Onboard mission manager software

In addition, numerous suppliers provided hardware installed throughout both spacecraft.

ASTRO and NextSat were deployed into a 492 x 492 km nominal orbit at 46° inclination. Ground control was conducted at the AFRL Research, Development, Test, and Evaluation Support Center (RSC) at Kirtland Air Force Base in Albuquerque, New Mexico. In addition, the Engineering Support Room (ESR) was established at the Boeing facility in Huntington Beach, California; and Rendezvous Support Room (RSR) at Boeing Tower 2 in Houston, Texas.

Figure 1.– ASTRO Mission Control Team in Albuquerque, New Mexico

Figure 2.– NextSat Mission Control Team in Albuquerque, New Mexico

During the first 24 hours after launch, ASTRO failed to achieve proper attitude control and sun-pointing, due to a software error associated with one of its three reaction wheels. NextSat was given control to point the mated stack for several days until a software update could be made and ASTRO could retake control. Following vehicle checkout, ASTRO and NextSat were put through the mated and unmated paces for four months. All mated and unmated mission objectives were achieved, the spacecraft were separated, and both vehicles were decommissioned on 22 July 2007. Orbit decay and de-orbit were anticipated within 25 years – first NextSat, then ASTRO.

Based on publicly-available information, OE accomplished a number of firsts in space. The most notable were:

- First autonomous rendezvous and capture from a range of 7 km
- First autonomous soft capture (during close stationkeep) of a satellite
- First autonomous robotic arm capture of a satellite
- First autonomous robotic transfer of a component from one vehicle to another
- First autonomous transfer of propellant from one vehicle to another
- First on-orbit use of an embedded IEEE 1394 (Firewire) spacecraft network

Note that the term *autonomous* on this program applied to an operation performed entirely in space without ground assistance.

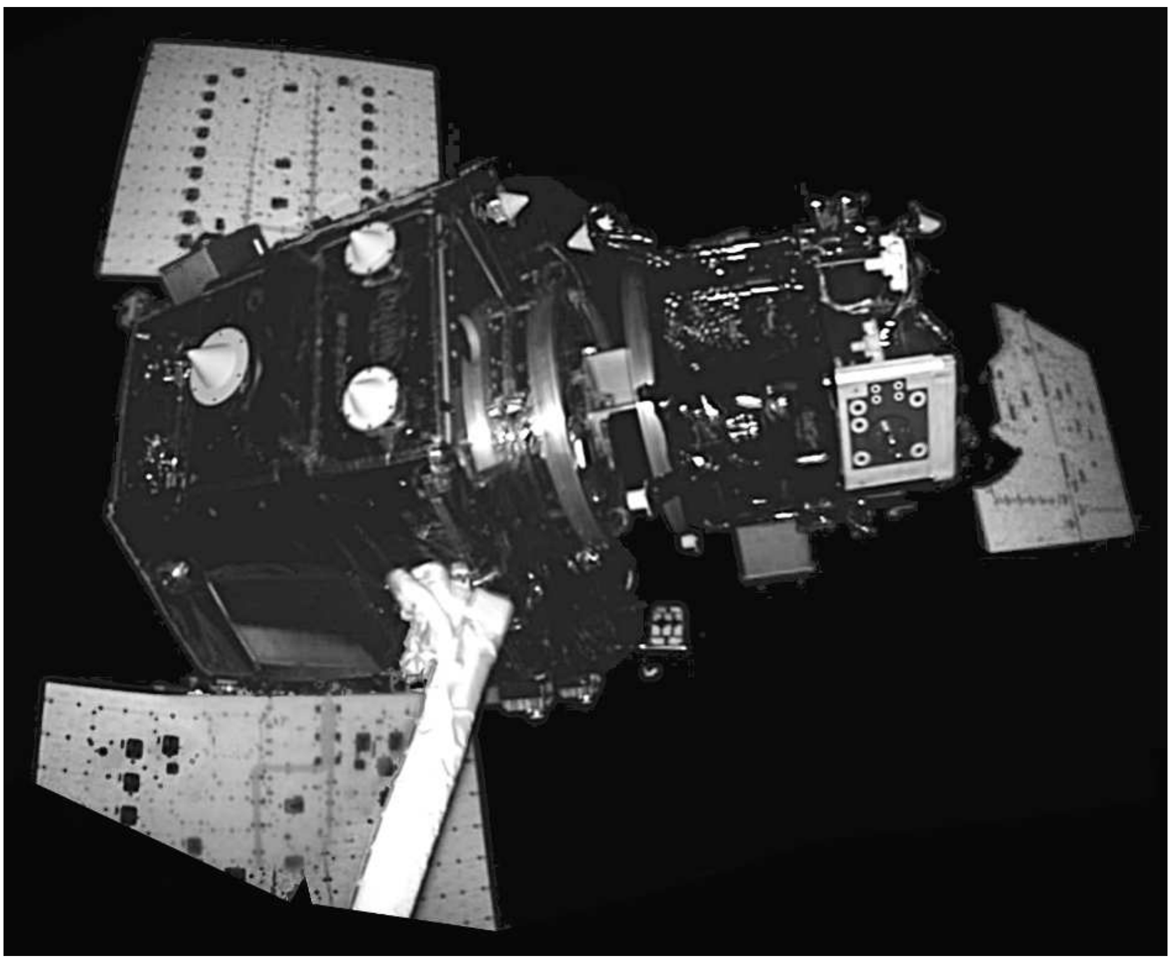

Figure 3.– Orbital Express Self-Portrait
Photographed by the Robotic Arm while ASTRO (Left) was Mated to NextSat (Right)

FLEXIBILITY TO SERVICE A VARIETY OF FUTURE SATELLITES

OE adhered to a top-level requirement to complete the demonstration program with confidence that servicing could be performed on any operational satellite containing the necessary open-system hardware interfaces. Emphasis was placed on accommodating client satellites in any orbit or desired attitude. To minimize impacts and costs to future satellite developers, complexity and mass burdens were levied upon the servicing spacecraft, not the client to be serviced. This approach permeated the program and was evidenced in the final design of ASTRO and NextSat hardware, software, and the flight test program during both mated and unmated operations. Here are examples of how the autonomous rendezvous and capture (AR&C) subsystem was designed to uniquely accommodate client satellite needs:

- Client need not "cooperate" with the servicer by transmitting its real-time navigation data
  - ➢ Inside 500 km and beyond the approach/departure corridor, ASTRO passively tracked NextSat using long- and mid-range cameras and software algorithms to compute relative position and velocity[1]
    - ▪ The Boeing Vision-based Software for Track, Attitude, and Ranging (Vis-STAR) and Autonomous Navigation (AutoNav) software used visible and infrared cameras to measure bearing angles at long range, and apparent NextSat size at mid-range
    - ▪ The Laser Range-Finder (LRF) provided precise range data at mid ranges
  - ➢ During corridor approach and capture, ASTRO used redundant and dissimilar passive sensors to compute relative position, velocity, attitude, and angular rate information
    - ▪ The NASA-MSFC/Orbital Sciences Corporation Advanced Video Guidance Sensor (AVGS) tracked NextSat-mounted long-range and short-range retro-reflectors
    - ▪ Vis-STAR supplied position and attitude data based on NextSat features
    - ▪ Options are available to the client to mount reflectors for maximum relative navigation robustness, or avoid the cost of retro-reflectors and rely on Vis-STAR natural feature tracking
- Client satellite can hold a preferred fixed or rotating attitude and the OE AR&C subsystem will perform approach and capture to that attitude
  - ➢ ASTRO executed three approaches while NextSat maintained a sun-pointing attitude (rotating in an earth frame)
  - ➢ Two approaches were made with NextSat in local horizontal local vertical (LVLH) hold attitudes
    - ▪ Exercise #2 approached from in front of NextSat (+V-bar), which is the direction the Space Shuttle docks with the International Space Station
    - ▪ Exercise #3 approached from above NextSat (-R-bar), which some client satellites may prefer (e.g., Boeing 702), to avoid interfering with nadir-pointing instruments
- Client satellite may choose to communicate a wave-off condition directly to the incoming servicer, or rely on the ground to wave-off the approach if the client isn't ready.
  - ➢ OE implemented crosslink health status communication from NextSat to ASTRO
  - ➢ During flight, the crosslink maximum range exceeded the 200 m specification
  - ➢ If NextSat could not hold a stable attitude during proximity operations, ASTRO would have been automatically notified and executed an abort
  - ➢ Ground was also prepared to command ASTRO abort if NextSat became no-go
  - ➢ NextSat no-go conditions did not occur during flight

- Client satellite need not take action to prevent collision
  - The OE system uses trajectories, mission manager abort commanding, and guidance collision avoidance algorithms to minimize collision probability[2]
  - Passively-safe trajectories were chosen for each OE exercise, keeping ASTRO on a non-intercept course except during the final minutes of approach inside 10 m
  - Subsystem monitoring kept the mission manager poised for abort commanding if a critical component failed within a specified timeframe
  - The guidance proximity abort mode was ready upon mission manager command, to execute a non-intercept trajectory to a safe stationkeep point 120 m from NextSat
  - Exercise #2 correctly, though unexpectedly, demonstrated abort commanding and collision avoidance to 120 m; resulting from a sensor processor failure during 10 m stationkeep
- Client satellite should encounter very low forces during capture
  - Instead of performing a docking that hits the client satellite with a positive closing rate, ASTRO stopped and stationkept a few centimeters from NextSat while the capture mechanism closed on the NextSat passive mechanism
  - Ball Aerospace observed very little translation and rotation rates imposed on NextSat during the five capture and matings
  - To minimize mass, power, and cost penalties of installing a capture device on a client satellite, the mechanism articulating elements and software reside on the servicer, leaving a simple, aluminum structure and proximity sensors to be installed on the client
  - The direct capture mechanism performed flawlessly during flight
- Client satellite should be given a choice of direct capture or robotic grapple and berth
  - If the servicing mission requires a robotic arm to install new components, the arm can also be used to execute grapple and berthing; which permits stationkeep at 0.8 m range
  - OE performed direct capture on the first three AR&C exercises, and grapple and berth on the final two
  - Grapple and berth operations were successful, but a script error and arm sensing problem required ground intervention to complete the berthing operation
- Client satellite should be able to specify a capture time
  - The OE guidance software, trajectory uploads, and procedures were designed to perform capture within a 10 minute window
  - Four out of five AR&C exercises performed capture within the window
  - Exercise #2 was on course to capture within the window, when a sensor processor failed, forcing an abort and capture on a later date

FLIGHT TEST PLAN

A flight test plan for mated and unmated operations was managed throughout the OE program. The plan called for multiple fuel transfers between ASTRO and NextSat, robotic transfer of a battery between spacecraft (also used for extra power on NextSat), and removal/replacement of an ASTRO computer (used as a backup sensor computer). In addition, the plan called for extensive autonomous rendezvous and capture (AR&C) operations that demonstrate an array of rendezvous trajectories, circumnavigation profiles, stationkeep distances, corridor approach directions, ground/TDRSS/crosslink communications, lighting angles, capture mechanisms, and abort types. These were treated as internal objectives that demonstrate virtually any reasonable means of rendezvousing, surveying, approaching, and capturing a satellite in need of repair. The plan served as a checklist as the mission unfolded, and a template to be followed if everything worked as planned with no onboard failures. The test plan was designed to walk - then run, as the AR&C subsystem was step-by-step unfolded, characterized, and adjusted as needed.

Given that ASTRO was equipped with reaction wheels, torque rods, space integrated GPS/INS (SIGI), star tracker, rotating solar arrays, ground and satellite communications, capture mechanism, robotic arm, AVGS, LRF, two batteries, three computers, three spotlights, five cameras, 16 thrusters, and a trainload of new-and-space-untested sensor and autonomous vehicle software, the team entered the flight prepared to deviate from, and improvise on, the test plan. Focus was placed on checking off program-level and internal objectives, while preventing any failures from becoming catastrophic to the mission.

To minimize risk of on-orbit hazard, and ground casualty after the two spacecraft eventually de-orbit, DARPA requested separation and unmated re-entry in accordance with USAF and USG policy. This would drive of an end-of-life (EOL) scenario leaving ASTRO and NextSat safely separated, without fuel, and in an unrecoverable state. During the days preceding EOL, DARPA also directed Boeing to fly ASTRO beyond sensor range and return; to characterize sensors and prove capabilities that ASTRO was designed for, at a very long range. This was to be followed by permanent departure, satellite decommissioning, and eventual orbit decay and de-orbit.

AR&C MISSION SUMMARY

The AR&C mission was a total success by meeting 100% of the mission objectives. The team learned a great deal from perfections and problems incurred along the way. The concept of starting mated and providing engineers with multiple opportunities to separate/capture the vehicles, assess, and make adjustments, worked extremely well. OE proved yet, again, that space is the only true laboratory for testing certain sensors and subsystems. Ground simulations and test stands are great, but not substitutes for the realities of the space environment.

AR&C exercise #1 (referred-to within the program as scenario 2-1) proceeded as planned. Ground instructions were uploaded four hours before demate, then ASTRO took it from there; executing autonomous demate, separation to 10 m, stationkeep, approach, and soft capture, over a period just under two hours. It represented the first U.S. execution of AR&C, and world's first AR&C without the target vehicle transmitting its own navigation state. (Details about all exercises are given below.)

The pre-flight test plan called for six additional AR&C exercises, taking ASTRO to greater ranges and executing more challenging operations. In reality, all AR&C objectives were met after just four more exercises. This was because exercise #2 (scenario 3-1) took the team further down the road than intended, due to hardware and software problems encountered along the way. During exercise #2, ASTRO flew to a maximum range of 6 km over eight days, rather than 30 m over two hours. While the walk-before-run approach came to an end, a great deal was learned, particularly about camera tracking and Kalman filtering at several kilometers range. These lessons learned were applied to subsequent exercises.

Exercises #3, #4, and #5 went very well, taking ASTRO to 120 m, 4 km, and 7 km; combined with three different flyaround inspection maneuvers, various stationkeep maneuvers, and capture performed directly and using the robotic arm. Sensor and AutoNav input adjustments were made following each exercise, particularly in optimizing which measurements should be ignored and which ones should be accepted. Successes and failures were observed during robotic arm grapple and berth operations in exercises #4 and #5. In both exercises, the arm grapple device correctly aligned itself and proceeded with capture without ground assistance. In exercise #4, a subsequent script error prevented autonomous berthing of NextSat to ASTRO and the ground had to intervene. In exercise #5, the device was so well aligned during grapple that the internal mousetrap device failed to trigger and arm continued moving inward until reaching a joint soft-stop. Again, no harm was done, but the ground had to intervene. This further demonstrated the benefits of working out the bugs through unmanned flight demonstration, particularly in an environment that cannot be exactly mimicked on earth.

Bonus objectives were met during EOL, when ASTRO departed 410 km behind NextSat and returned to 500 m in front. Along the way, ASTRO held itself for nearly a day between 500 m and 1 km behind NextSat in a low-fuel-expenditure mode. During this standoff period, the laser rangefinder failed and AVGS was unavailable given the NextSat attitude, so NextSat range was derived from angle data supplied by ASTRO camera tracking software. After flying the DARPA-directed detour, ASTRO flew 15 km above and drifted behind while the long-range camera tracked beyond 500 km – exceeding the 200 km specification for that sensor. Before EOL, ASTRO had 127 of 144 kg usable fuel remaining (88%). At the end of all translation maneuvers, ASTRO had 98 kg usable fuel remaining (68%), which was burned and vented overboard to prevent possible pressure build-up and explosion later.

AR&C EXERCISE #1 (SCENARIO 2-1): 6 MAY 2007 (UTC)

Exercise #1 Plan

AR&C exercise #1 was designed to execute rendezvous and capture at close range without ground assistance, and without incurring excessive risk. The onboard system was armed to execute an abort, if warranted. Ground communication was reserved for nearly the entire unmated duration, so the ground could command an abort if conditions warranted, and the onboard mission manager failed to perform. This was the first time ASTRO would fully detach from NextSat.

- Maximum range = 12 m
- Unmated $1^h\ 53^m\ 29^s$ within $\pm 5^m$
  - Ground instructions uploaded to ASTRO at approximately demate minus 4^h
  - Onboard-controlled pre-demate power-up sequence
  - ASTRO to free drift attitude
  - Demate (UTC): 6 May 2007 at $5^h\ 22^m\ 36^s$
  - Capture mechanism release
  - Night demate over COOK AFSCN site
  - Corridor separation to 10 m
  - Stationkeep for nearly 1 orbit
  - Corridor approach
  - Night direct capture & mate over BOSS
  - ASTRO/NextSat to solar inertial attitudes

Figure 4 shows the exercise #1 anticipated ASTRO and NextSat groundtrack.

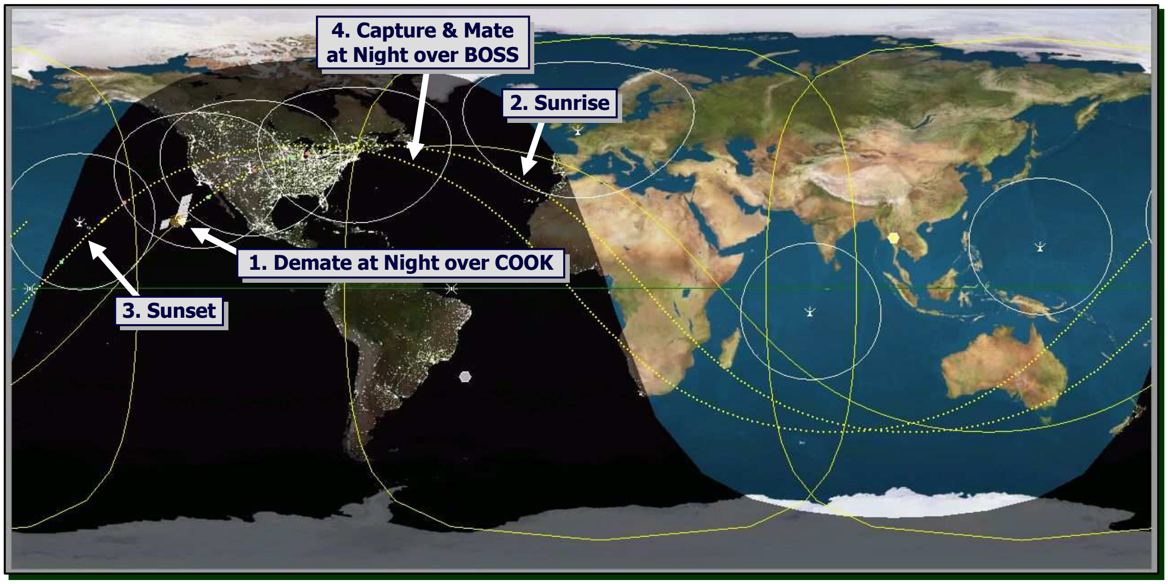

Figure 4.– Exercise #1 Planned Groundtrack
(Simulated with BSTAMPS/SimWorks)

Figures 5 and 6 depict ASTRO anticipated in-plane and out-of-plane relative motion in a NextSat-centered local vertical curvilinear (LVC) coordinate frame.

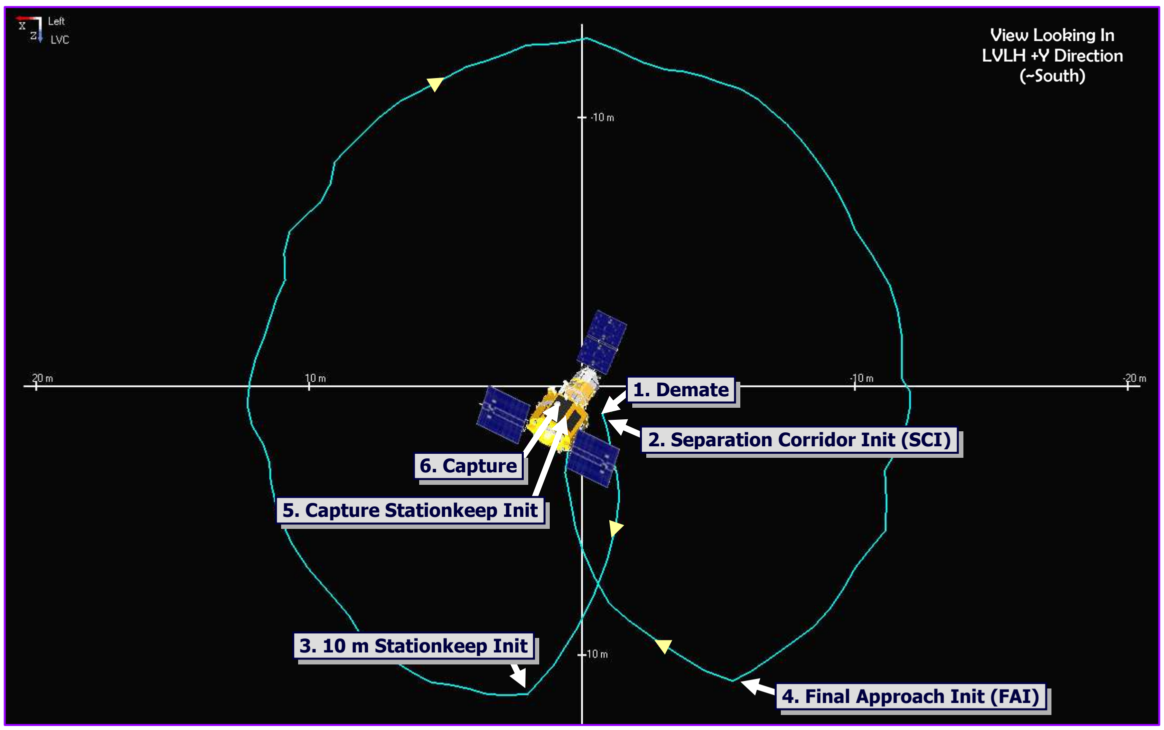

Figure 5.– Exercise #1 Planned In-Plane Relative Trajectory
(Simulated with BSTAMPS/SimWorks)

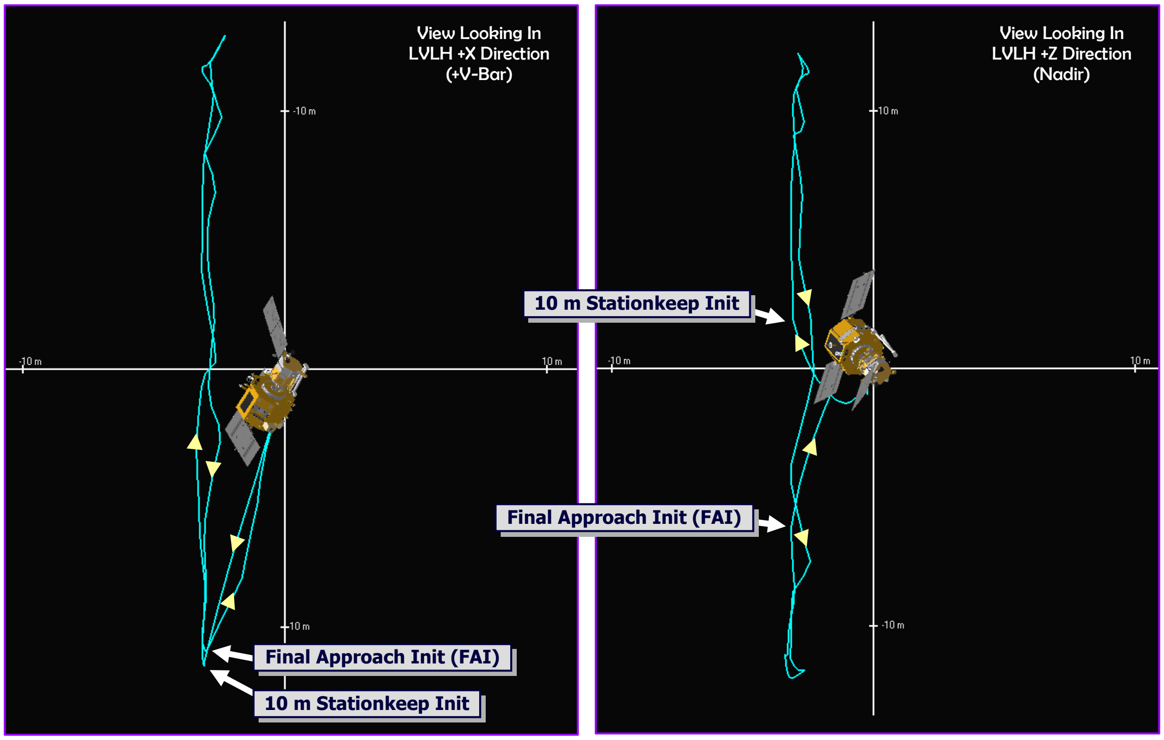

Figure 6.– Exercise #1 Planned Out-of-Plane Relative Trajectory
(Simulated with BSTAMPS/SimWorks)

Exercise #1 Results

Based on publicly-available information, OE demonstrated the first U.S. AR&C and world's first AR&C without the target vehicle transmitting its navigation state. The trajectory almost exactly matched the output generated by the Boeing Spacecraft Trajectory Analysis and Mission Planning Simulation (BSTAMPS), as visualized in SimWorks, with capture and mate occurring inside the 10 minute window. Ground personnel tracked telemetry data and observed real-time video, but did not need to intervene.

Approximately four hours before demate, ground controllers uploaded instructions and handed over ASTRO control to the onboard mission manager, which powered on sensors and other equipment during countdown to demate. ASTRO held the combined ASTRO/NextSat stack in solar inertial attitude until demate minus 10 seconds, when pointing guidance and flight control entered free drift. At the designated demate time, the mission manager commanded the ASTRO capture mechanism to release NextSat. About 2 minutes later, ASTRO was clear of NextSat and guidance was commanded to target track attitude and corridor separation.

Guidance, navigation, control, and propulsion flew a flawless trajectory while NextSat held to its last attitude. ASTRO did not hit the separation corridor boundary, required very few burns to maintain the truncated-cone-shaped stationkeep box that extended from 10 to 12 m, and bounced off the approach corridor only once. Propellant usage was slightly less than simulations predicted.

Meanwhile, ground controllers compared live camera video (i.e., truth) against telemetry-driven graphics displays and concluded onboard relative navigation was accurate. Given this and the positive states seen by ASTRO and NextSat subsystems, ground control concurred with the mission manager assessment that there was no need for an abort.

When ASTRO returned and entered the capture stationkeep box, all capture mechanism constraints were met, and the mission manager immediately commanded the capture mechanism to close. ASTRO continued to maintain position and attitude during closure and executed one jet firing near the end of the 10 second period to avoid getting too close to NextSat. Upon capture, the mission manager, guidance, capture, flight control, and NextSat ground controllers simultaneously declared positive readings based on telemetry displays. ASTRO immediately entered free drift, the vehicles were mated, and ASTRO rotated the stack to point all arrays at the sun. This all took place without ground assistance.

The benefit of having redundant, dissimilar sensors was confirmed as AVGS provided accurate and uninterrupted relative navigation data, while Vis-STAR supplied partial data. The wide field-of-view (WFOV) visible camera supplying data to Vis-STAR, only tracked NextSat inside 2 m and beyond 9 m. This was attributed to the camera adjusting itself to a brighter-than-expected image, due to a spotlight reflection coming from the DARPA reflective logo attached to the face of NextSat. A software setting was adjusted and problem resolved in time for AR&C exercise #2. In addition, the infrared camera supplied good angle data but not NextSat attitude. This problem, too, was resolved in time for exercise #2 with a software input update.

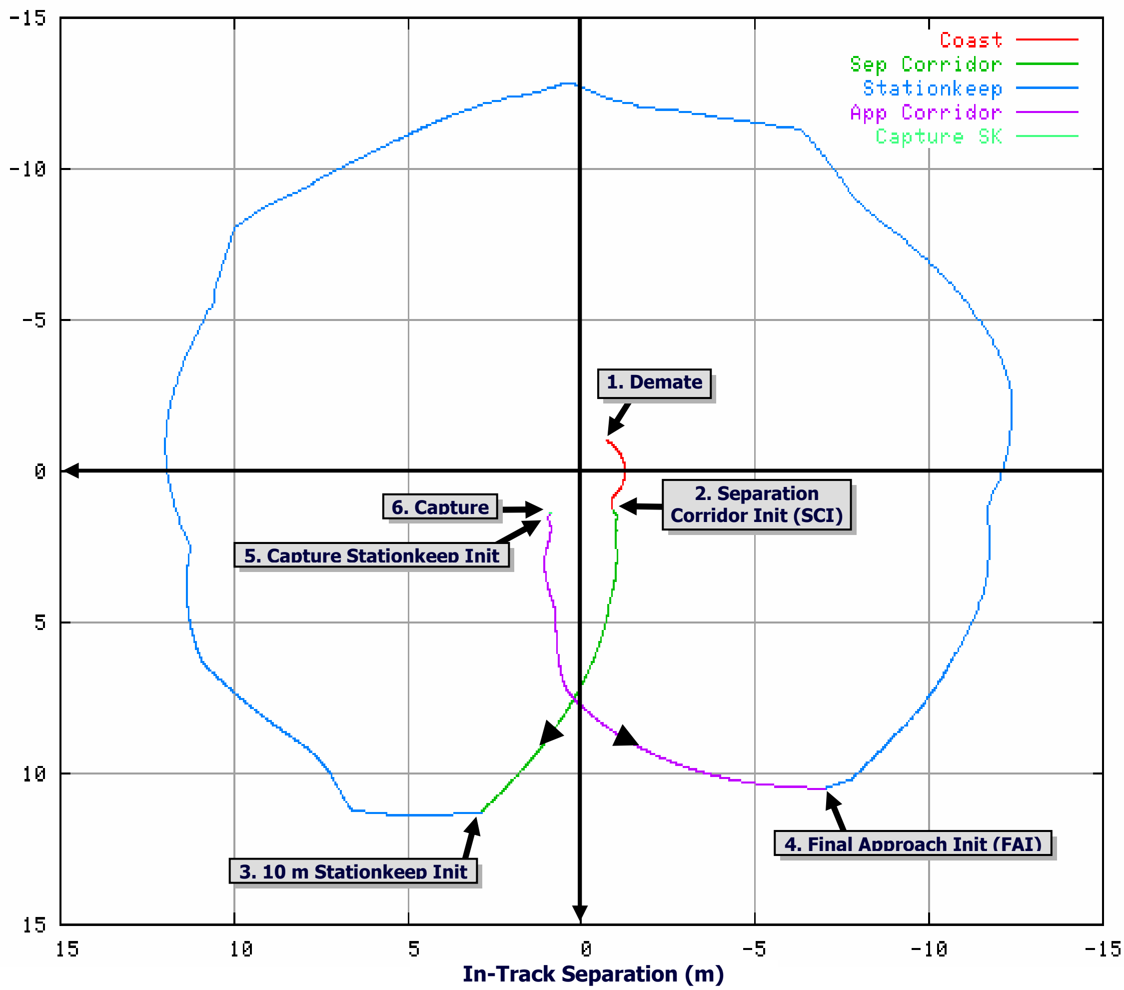

Figure 7.– Exercise #1 Actual/Onboard In-Plane Relative Trajectory

Exercise #1 Summary

- Maximum range = 12 m
- Unmated for $1^{h}\ 57^{m}\ 5^{s}$
  - Demate (UTC): 6 May 2007 at $5^{h}\ 22^{m}\ 36^{s}$
  - Capture initiation: 6 May at $7^{h}\ 17^{m}\ 51^{s}$
  - Mate: 6 May at $7^{h}\ 19^{m}\ 41^{s}$
- Propellant use = 0.3 kg
  - Pre-exercise estimate = 0.4 kg

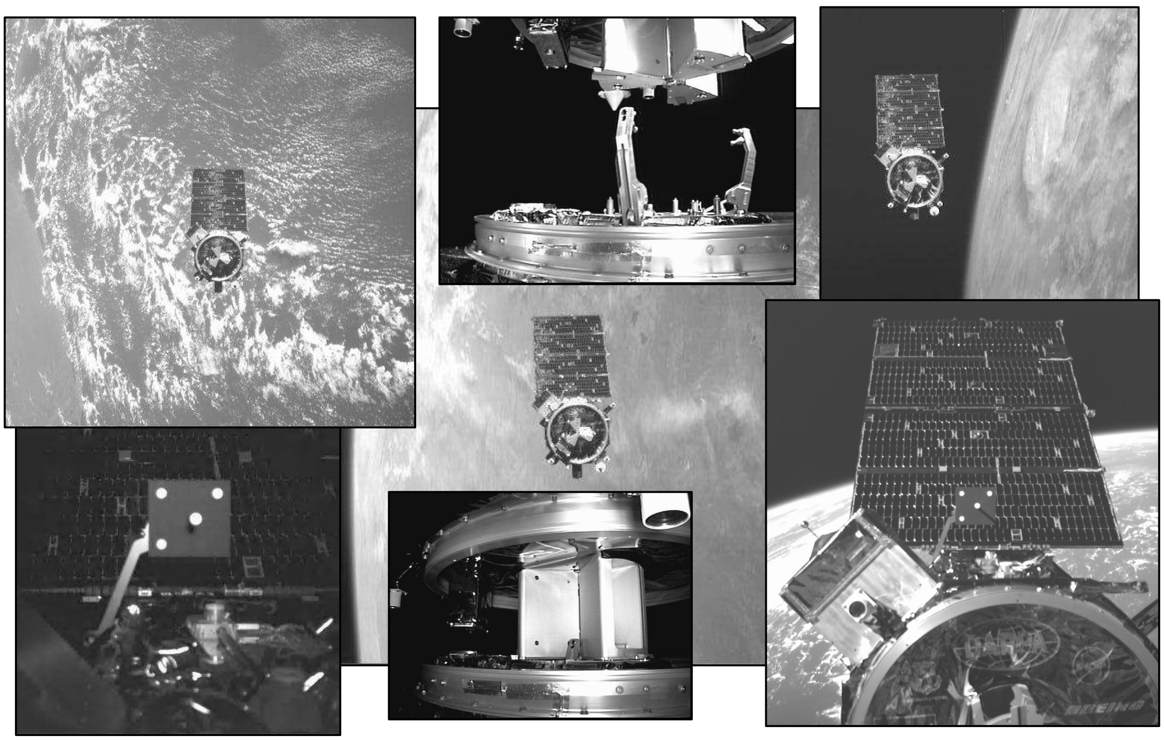

Figure 8.– Exercise #1 Photos

AR&C EXERCISE #2 (SCENARIO 3-1): 12-20 MAY 2007 (UTC)

Exercise #2 Plan

The intent of AR&C exercise #2 was to take another step forward by expanding sensor track testing to 30 m, and using the robotic arm to grapple and berth NextSat for the first time.

- Maximum range = 30 m
- Unmated $2^{h}\ 8^{m}\ 16^{s}$ within $\pm 5^{m}$
  - Nighttime demate over COOK
  - Separate to 30 m
  - Initial approach to 10 m
  - Stationkeep for less than 1 orbit
  - Final Approach
  - Nighttime robotic grapple capture & berth over BOSS

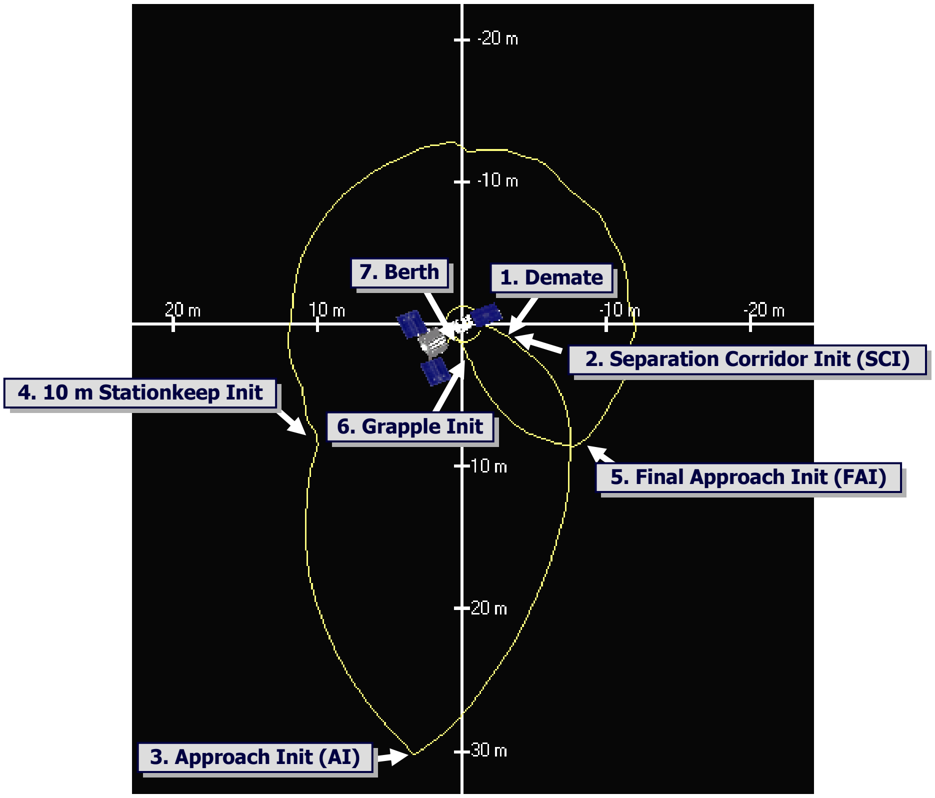

Figure 9.– Exercise #2 Planned In-Plane Relative Trajectory
(Simulated with BSTAMPS/SimWorks)

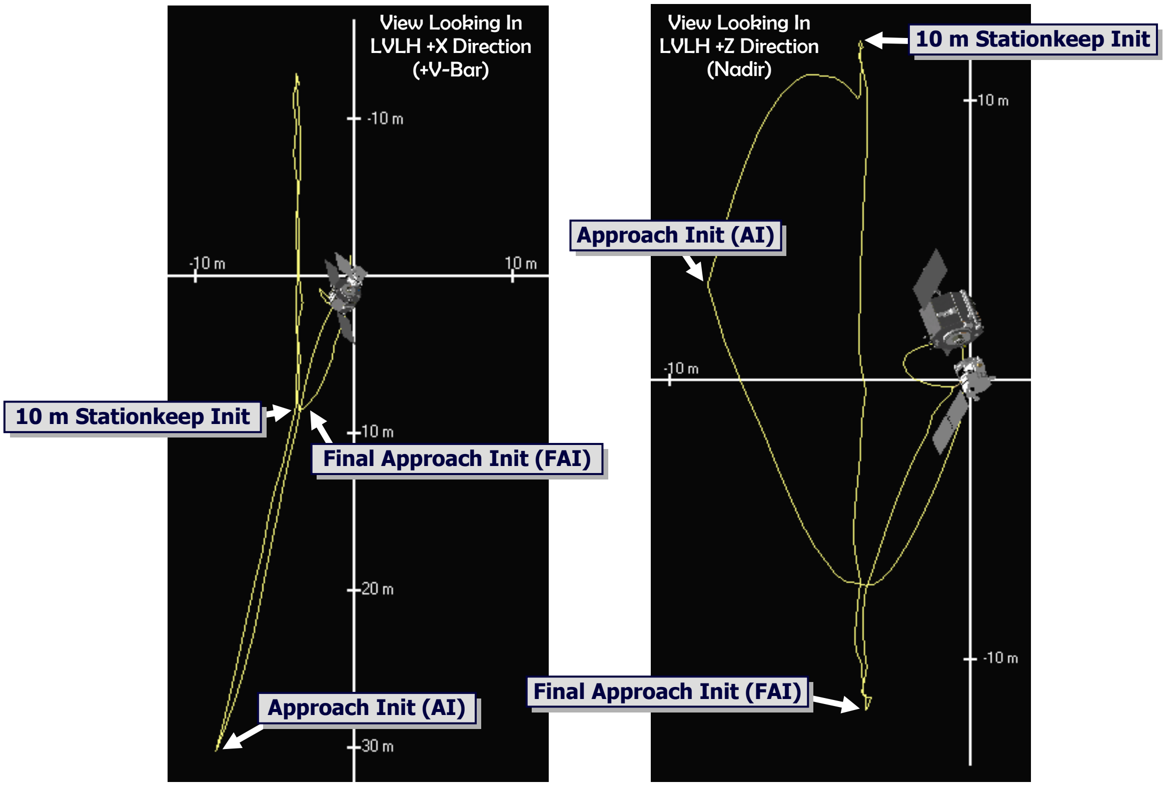

Figure 10.– Exercise #2 Planned Out-of-Plane Relative Trajectory
(Simulated with BSTAMPS/SimWorks)

Exercise #2 Results

AR&C exercise #2 began smoothly as ASTRO separated to 30 m and returned to 10 m stationkeep. Unlike exercise #1, ASTRO cameras tracked NextSat the entire time. Relative navigation was dead-on, given Vis-STAR data from multiple cameras and AVGS tracking of long- and short-range retro-reflectors (depending on range).

As the ground team settled in, notification appeared that the onboard mission manager detected failure of the sensor processor within the sensor computer (problem #1). Post-exercise evaluation was inconclusive as to the cause of failure, though hardware was suspected. This was because the backup computer executed the same software load as the primary computer for the remainder of the mission, without failure.

At close range, any type of sensor computer failure is cause for abort, and the mission manager correctly instructed rendezvous guidance to fly to a safe hold point. Guidance flew ASTRO along a separation corridor to ~35 m, back to 120 m behind NextSat, and into a stationkeep box, where the mission manager awaited further instructions from the ground. The computer failure took Vis-STAR down, but AVGS continued tracking NextSat until the retro-reflector off-angle exceeded ~30° after leaving the separation corridor at a range of ~45 m. From ~45 to 120 m range, relative navigation slowly degraded as ASTRO propagated the last known NextSat state. Figure 10 compares the trajectory generated by BSTAMPS in blue against the trajectory flown with onboard navigation, in red. (Gaps in this and other trajectory plots occurred during periods with no ground communication with ASTRO.)

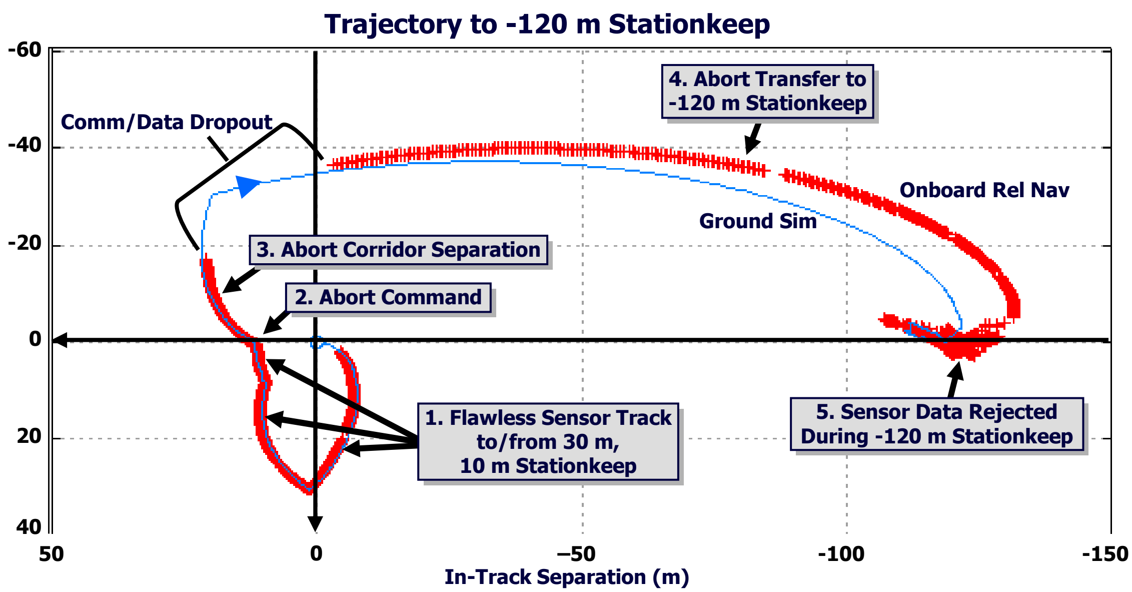

Figure 11.– Exercise #2 Planned/Simulated and Actual/Abort Relative Trajectories

During transfer to –120 m, ground controllers rebooted the primary sensor computer, but failed to recover the sensor processor. The backup sensor computer was then booted, at about the time of stationkeep initiation, and the Infrared camera resumed NextSat tracking. Unfortunately, some readings indicated were very short distances. This problem was later attributed to "hot" pixels – a problem that was later avoided through sensor input parameter updates. Given the disparity between sensor measurements and propagated states, the relative navigation filter rejected Vis-STAR inputs (problem #2). 120 m is a safe distance without relative navigation for awhile, but after about one hour of stationkeep, the ground chose to break out of stationkeep and permit ASTRO to drift further behind. The coast command went up and ground observed NextSat drift ahead, ready to nudge ASTRO higher, if necessary to ensure an opening rate.

The ground team allowed ASTRO to drift overnight without relative navigation data, while the Air Force performed ranging on NextSat, which was not equipped with a GPS unit. By the following afternoon, ASTRO had coasted beyond 2.4 km behind NextSat and the ground decided it was time to arrest the opening rate, as it continued to evaluate the relative navigation problem.

Similar types of contingency situations were conjectured pre-flight and a set of small external delta-velocity (EXDV) LVLH burns, referred to as *nudge burns*, were pre-loaded aboard ASTRO. The ground chose to execute a –X nudge that should have imparted a single retrograde pulse of –0.01 m/s. Instead, an erroneous delta velocity of –0.06, 0.14, 0.37 m/s incurred (problem #3). This problem was traced to a guidance software issue associated with the Space-Integrated GPS/INS (SIGI). The anomalous behavior had not been observed previously, either on orbit or in simulation. (After exercise #2, the ground diagnosed, fixed, and flight-tested the nudge burn to make it available for contingency use later, should conditions warrant.)

At this point, the ground was uncertain what the new relative orbit was and decided it best to wait for good lighting when NextSat would hopefully appear in the narrow field-of-view (NFOV) camera. In the meantime, the Air Force would perform NextSat ranging. NextSat did, in fact, appear in NFOV camera during a ground contact. It turned out not to appear as a dot, but a disk. This meant the nudge burn was, in fact, retrograde, though larger than intended. Given uncertainties surrounding ASTRO's exact orbit and nudge burn reliability, the ground decided to permit ASTRO to coast from behind to in front of NextSat.

After many hours passed, ASTRO reached ~6 km in front of NextSat with a relative orbit shaped like a large football and somewhat out-of-plane from NextSat's orbit. A posigrade burn was executed to arrest the opening rate, but this time by firing individual thrusters, as was done during thruster checkout. ASTRO coasted in a safe and stable orbit while pointing at the point where it believed NextSat existed.

While the situation was a far-cry from that planned for exercise #2, and the walk-then-run approach that was laid out for the mission, it did represent a true environment to evaluate camera and LRF performance under natural, variable lighting conditions. For example, sun glare on camera lenses was more pronounced than that observed during lab testing with a sun gun. Also, an occasional LRF return would indicate a range in the neighborhood of 14 km. During the next several days, the ground iterated on sensor and AutoNav settings to improve performance. Some settings upset the navigation state, but no harm was done since ASTRO was coasting, and the ground team simply needed to uplink new target state updates.

After improvements were seen with infrared camera tracking, and a few returns were received from LRF firings, DARPA directed Boeing to proceed closer to NextSat, load new guidance sequences, approach NextSat from in front (+V-bar) and perform direct capture. Boeing proceeded with this plan, was able to get continuous infrared camera track, LRF track inside ~2.5 km, and AVGS track inside ~150 m. During corridor initial approach, a nadir right-side thruster that fired frequently, became warm and approached its temperature limit, but cooled off as the sun neared orbital noon.

In summary, exercise #2 was certainly a stressing case, as two hours turned into eight days. Given ASTRO's excursions, particularly with the erroneous burn, propellant use was several times what was planned. But autonomous collision avoidance was validated, sensors were characterized, and the Kalman filter was better understood. This exercise was certainly a valuable learning experience.

Exercise #2 Summary

- Maximum range = 6 km
- Unmated for $7^d\ 22^h\ 25^m\ 30^s$
  - Demate (UTC): 12 May 2007 at $4^h\ 28^m\ 52^s$
  - Direct capture initiation: 20 May at $2^h\ 52^m\ 30^s$
  - Mate: 20 May at $2^h\ 54^m\ 22^s$
- Propellant use = 4.1 kg
  - Pre-exercise estimate = 0.8 kg

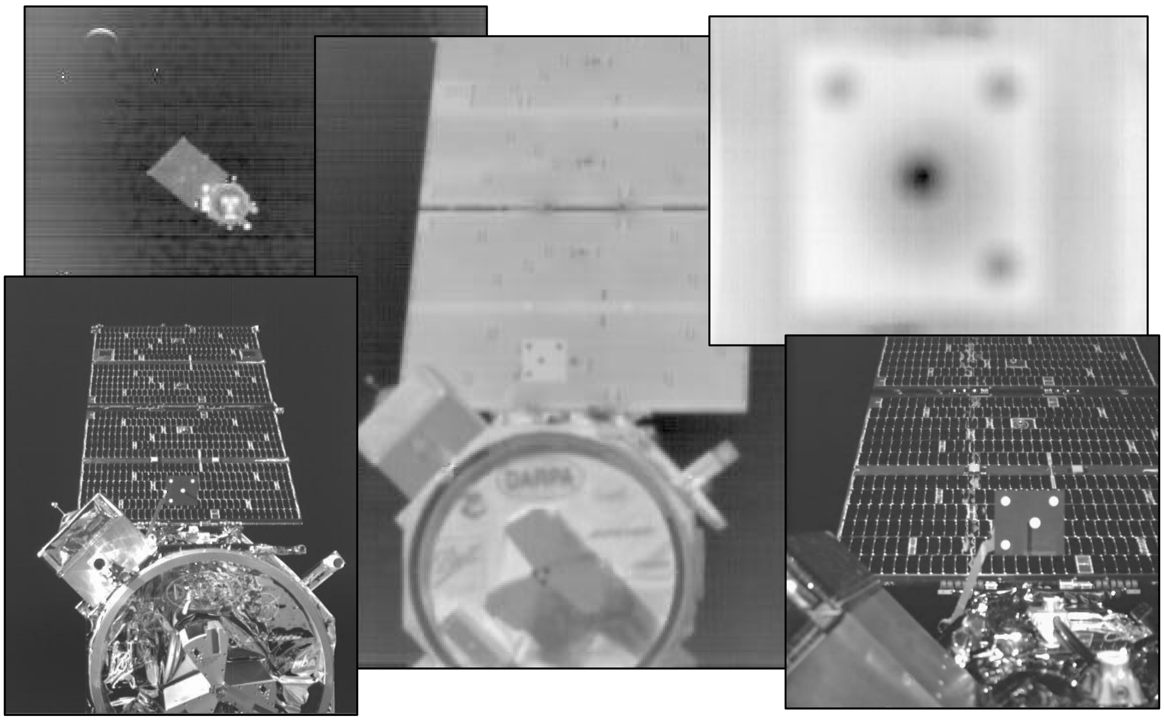

Figure 12.– Exercise #2 Photos

AR&C EXERCISE #3 (SCENARIO 5-1): 16 JUNE 2007 (UTC)

Exercise #3 Plan

Boeing studied the problems that occurred during exercise #2 and DARPA held an in depth readiness review with an independent evaluation team, prior to approving exercise #3 demate. Particular focus was on the sensor computer failure, camera tracking, AutoNav acceptance of data, and the nudge burn. For exercise #3, DARPA and Boeing chose the backup sensor computer, as it worked fine during exercise #2. Changes in AutoNav settings were approved, and the nudge burn logic was modified to place ASTRO into coast for one second before the EXDV was applied. A nudge test was successfully performed while mated, before exercise #3, permitting a nudge burn to be used, if necessary.

During the 27 days of mated operations, a new sensor software build and AutoNav inputs were uplinked to ASTRO. Given the long distances exhibited by exercise #2, objectives were already met for the 60 m case, so it was skipped in favor of the next test of a ±120 x 60 m natural motion flyaround, and NextSat approach from above. Direct capture was chosen over robotic grapple and berth. The solar beta angle had dropped to near-zero, creating a relatively large crosstrack distance during corridor separation.

- Maximum range = 120 m
- Unmated $4^h\ 46^m\ 54^s$ within $\pm 5^m$
  - Daylight demate over LION with sun β = –3.3°
  - Solar inertial separation to 70 m below/right of NextSat
  - Large 47 m crosstrack
  - ±120 x 60 m in-plane elliptical flyaround
    - Natural motion with correction burns as needed
    - Single-orbit rate
  - +120 m stationkeep
  - –R-bar approach
  - Direct capture
  - Daylight mate with TDRSS with sun β = –2.6°

Exercise #3 Results

Performance was nominal. During the flyaround, AVGS lost lock when NextSat exceeded a 27° off-angle, as expected, which occurred at a range of 98 m. Vis-STAR tracked nearly the entire time, including approach from above with earth background. LRF provided nearly 100% accurate returns, with inaccurate ones being way off and rejected by AutoNav. Batteries on both vehicles remained mostly charged, despite taking them out of solar inertial attitude to perform the –R-bar approach. Thrusters did not approach their temperature limits, as they had during exercise #2 (nor did they during the remainder of the mission). Propellant use was less than simulation. Unlike exercise #1, no jet firings were needed during 10 seconds of active guidance inside the capture box. The capture mechanism worked well. NextSat held solar inertial and R-bar attitudes very well. Not surprisingly, the corridor approach velocity was on the slow side, due to R-bar orbital mechanics. This resulted in capture and mate near the end of the 10-minute window.

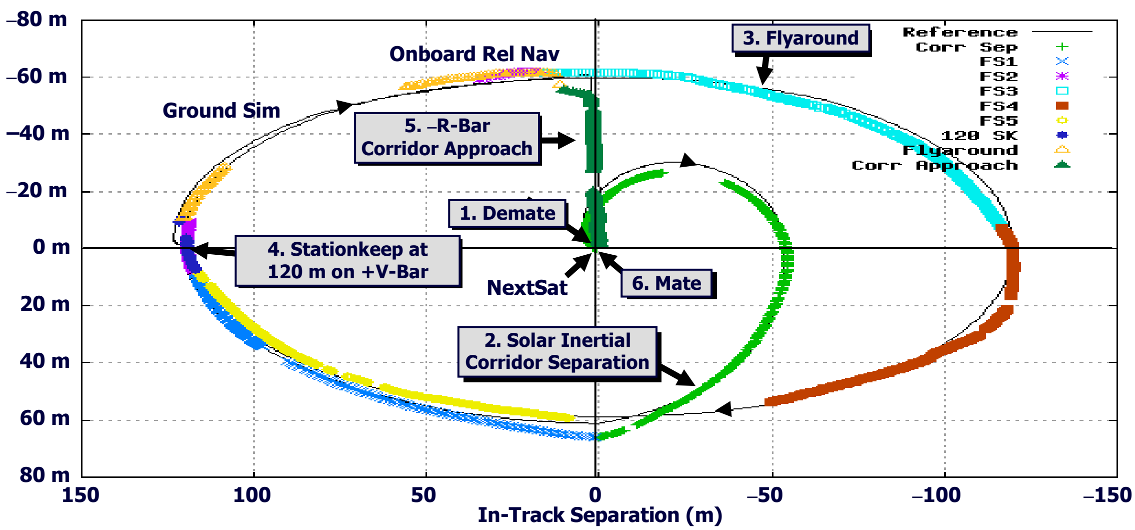

Figure 13.– Exercise #3 Planned and Actual In-Plane Relative Trajectories

Exercise #3 Summary

- Maximum range = 120 m
- Unmated for $4^h\ 51^m\ 7^s$
    - Demate (UTC): 16 June 2007 at $9^h\ 47^m\ 2^s$
    - Direct capture initiation: 16 June at $14^h\ 36^m\ 22^s$
- Propellant use = 1.4 kg
    - Pre-exercise estimate = 2.2 kg

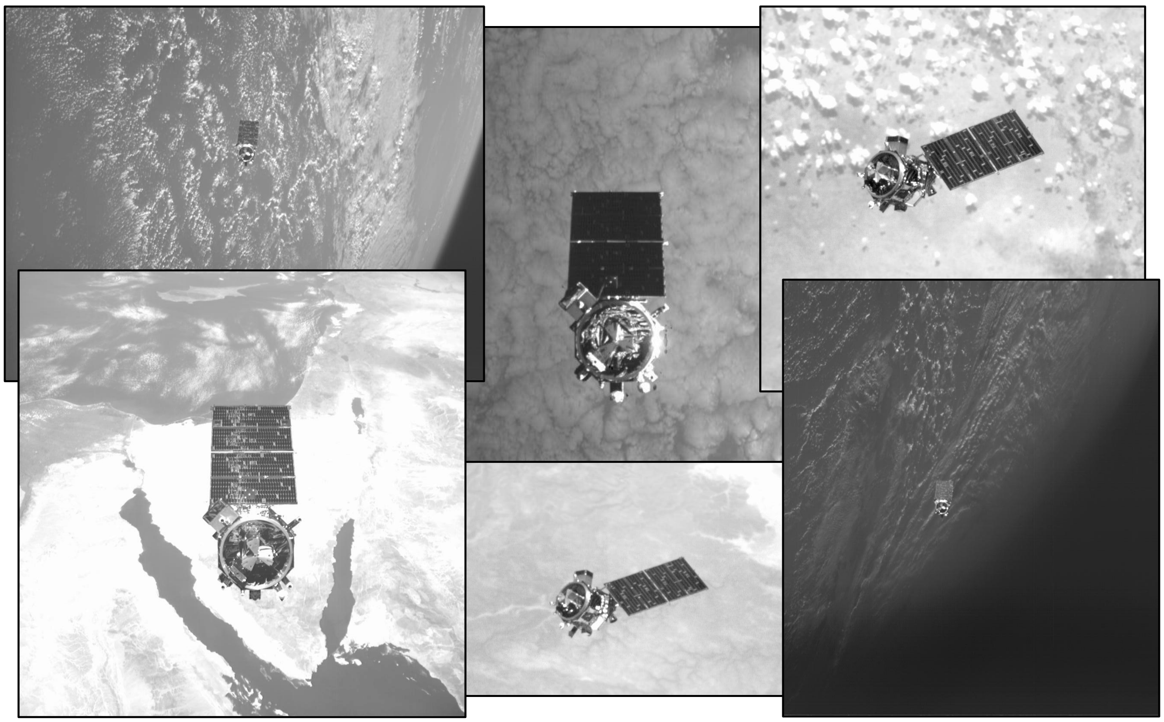

Figure 14.– Exercise #3 Photos

AR&C EXERCISE #4 (SCENARIO 7-1): 23 JUNE 2007 (UTC)

Exercise #4 Plan

Because exercise #2 successfully demonstrated a +V-bar approach, another scenario was skipped, this time in favor of a newly-designed trajectory to 4 km behind NextSat and back, again. During proximity operations, ASTRO would execute a 100 m near-circular forced-motion flyaround at single-orbit rate, targeting 8 waypoints along the way. Because a robotic grapple and berth had still not been attempted, this would be the first attempt. Given the time-of-year, it was no longer nighttime as ASTRO flew over the continental U.S. This dictated that grapple be scheduled over a single AFSCN pass, since the arm camera preferred controlled lighting that accompanies night with a spotlight. A 9-minute REEF pass was chosen, which meant that if grapple occurred near the end of the 10-minute window, ground controllers would have TDRSS coverage and, therefore, data, only.

- Maximum range = 4 km
- Unmated $16^h\ 45^m\ 59^s$ within $\pm 5^m$
    - Daylight demate over GUAM with sun $\beta = 24.6°$
    - Solar inertial separation to 130 m above NextSat

- Phasing to –4 km (behind NextSat)
- Return to –120 m V-bar stationkeep
- 100 m near-circular flyaround
- Forced-motion, in-plane inspection
- Single-orbit rate
- +120 m V-bar stationkeep
- Transfer to 60 m corridor
- Solar inertial approach

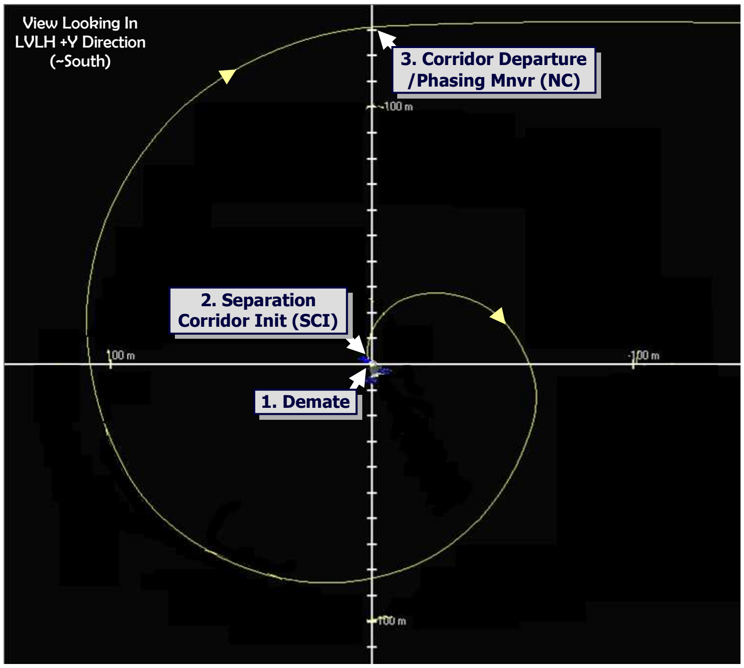

Figure 15.– Exercise #4 Planned In-Plane Corridor Separation Trajectory
(Simulated with BSTAMPS/SimWorks)

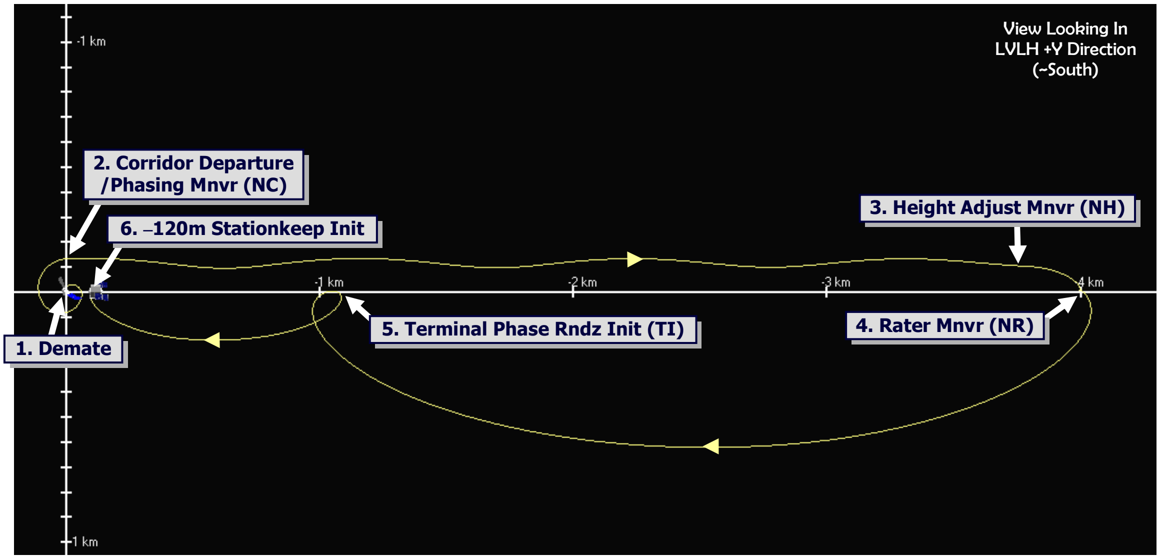

Figure 16.– Exercise #4 Planned In-Plane Rendezvous Trajectory
(Simulated with BSTAMPS/SimWorks)

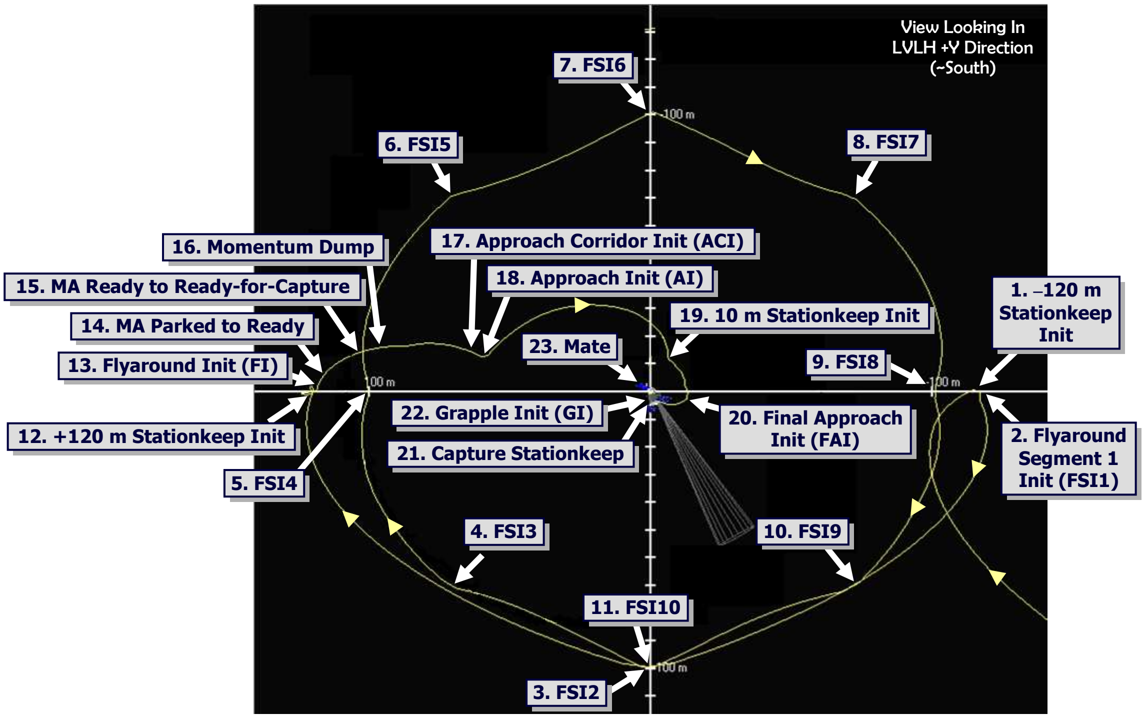

Figure 17.– Exercise #4 Planned In-Plane Proximity Operations Trajectory
(Simulated with BSTAMPS/SimWorks)

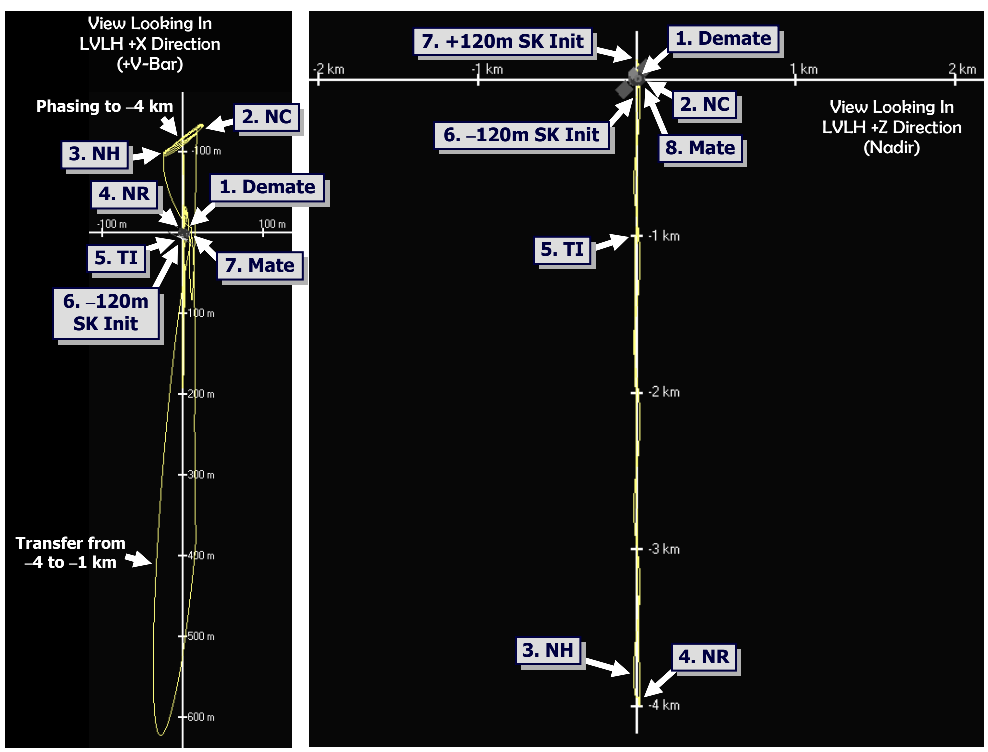

Figure 18.– Exercise #4 Planned Out-of-Plane Relative Trajectory
(Simulated with BSTAMPS/SimWorks)

Exercise #4 Results

The operation was nominal through grapple, executing the world's first autonomous grapple in space. Grapple occurred near the end of the designated 10-minute window. This coincided with the end of the REEF pass, and video and data were lost before confirming that grapple had occurred. Telemetry returned via TDRSS a short time later, indicating that NextSat was, in fact, captured. Autonomous berth was also scheduled, but interrupted by the onboard mission manager due to a berthing script error. So berthing was accomplished with ground assistance, requiring over five hours to complete.

AVGS tracked well within close range. Vis-STAR and LRF performed well at close and long range. Guidance, navigation, and control continued to perform well. NextSat performance was nominal. Fuel use was somewhat less than simulations.

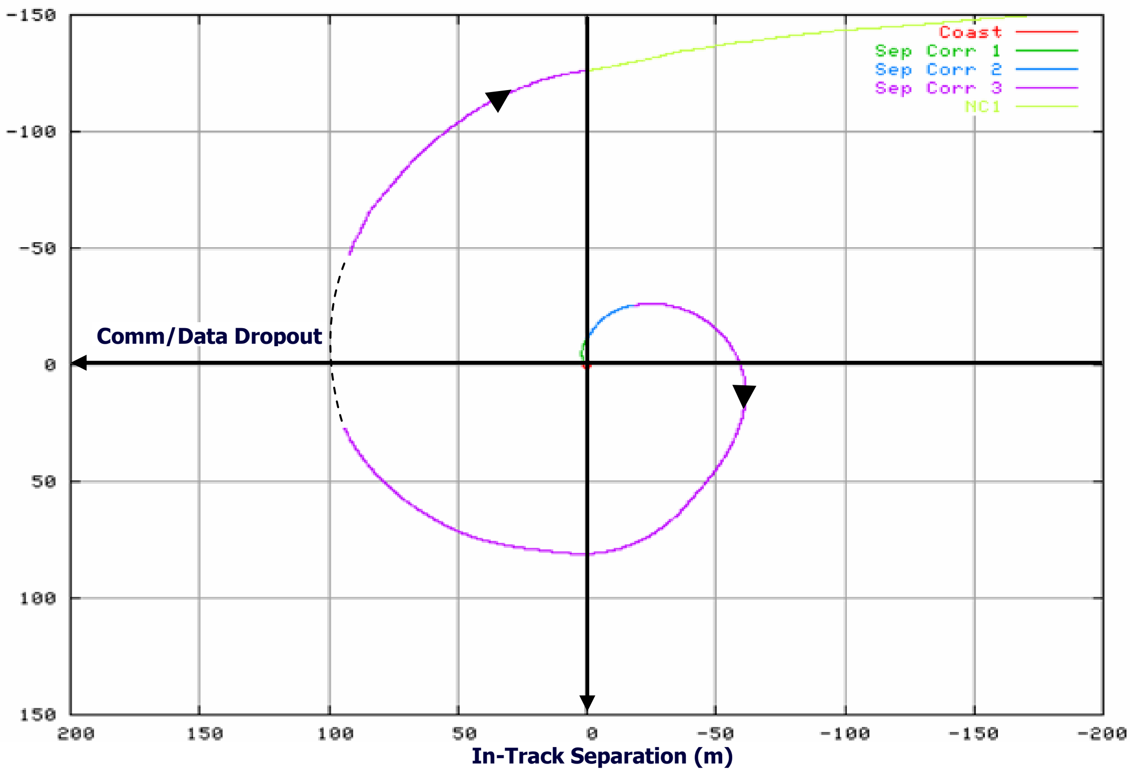

Figure 19.– Exercise #4 Actual/Onboard In-Plane Corridor Separation Trajectory

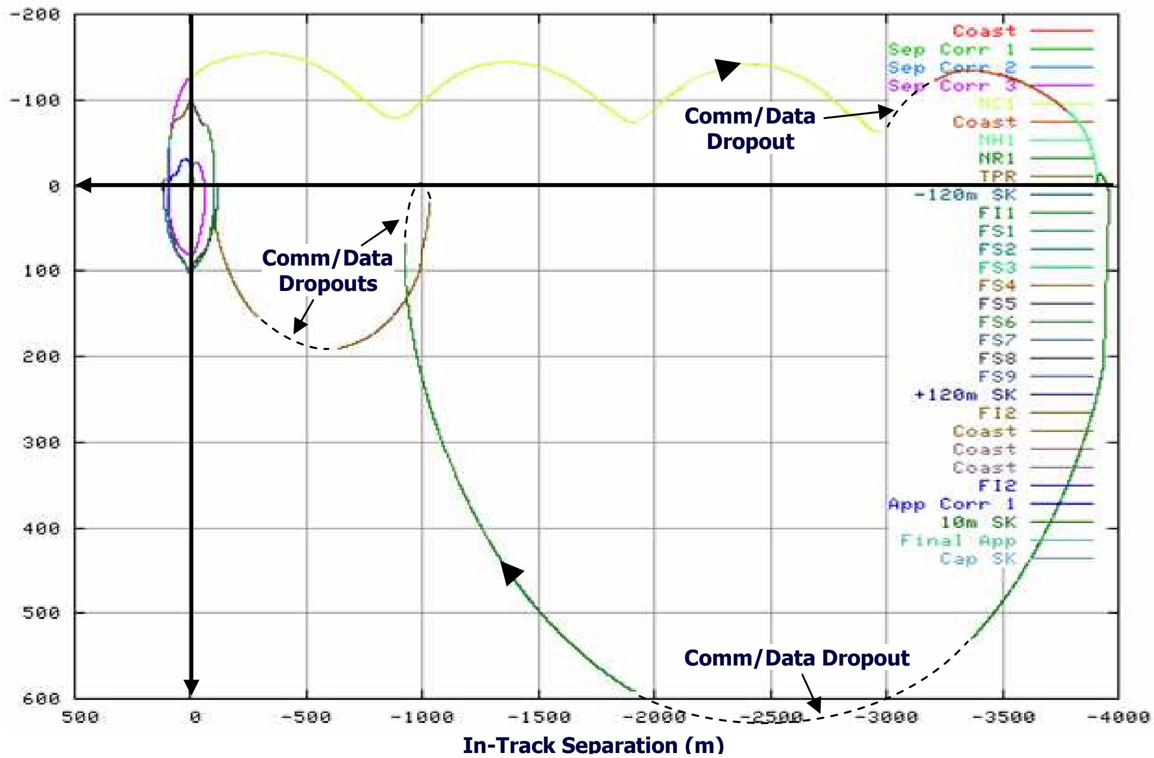

Figure 20.– Exercise #4 Actual/Onboard In-Plane Rendezvous Trajectory

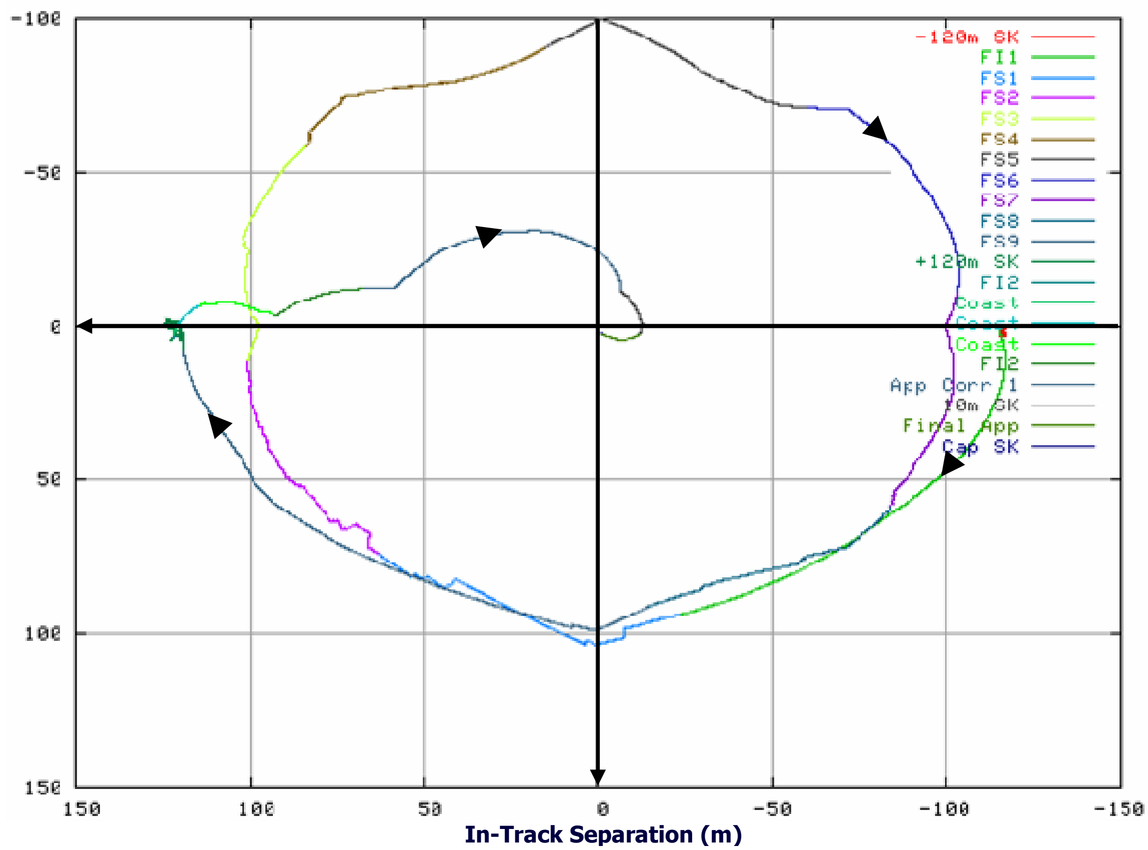

Figure 21.– Exercise #4 Actual/Onboard In-Plane Flyaround and Approach Trajectory

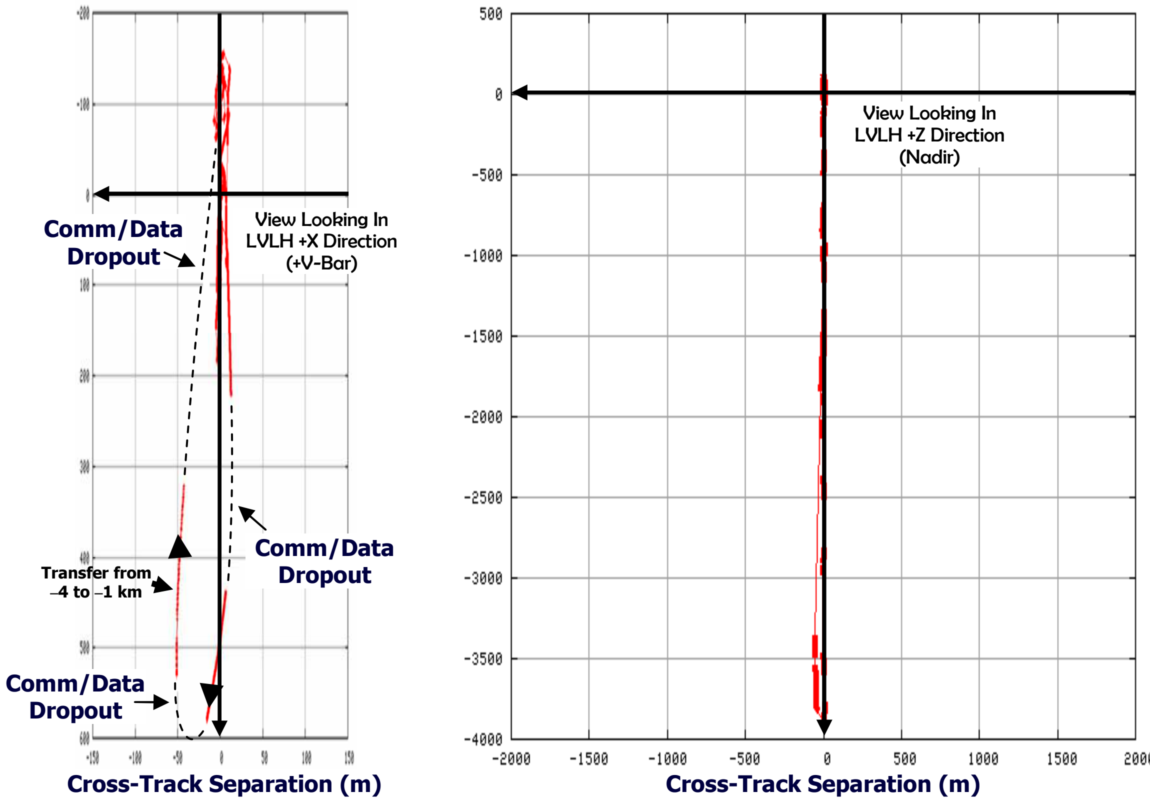

Figure 22.– Exercise #4 Actual/Onboard Out-of-Plane Relative Trajectory

Exercise #4 Summary

- Maximum range = 4 km
- Unmated for $22^h\ 2^m\ 19^s$
  - ➢ Demate (UTC): 23 June 2007 at $0^h\ 55^m\ 42^s$
  - ➢ Direct capture initiation: 23 June at $17^h\ 37^m\ 38^s$
  - ➢ Mate: 23 June at $22^h\ 58^m\ 1^s$
- Propellant use = 3.7 kg
  - ➢ Pre-exercise estimate =3.8 kg

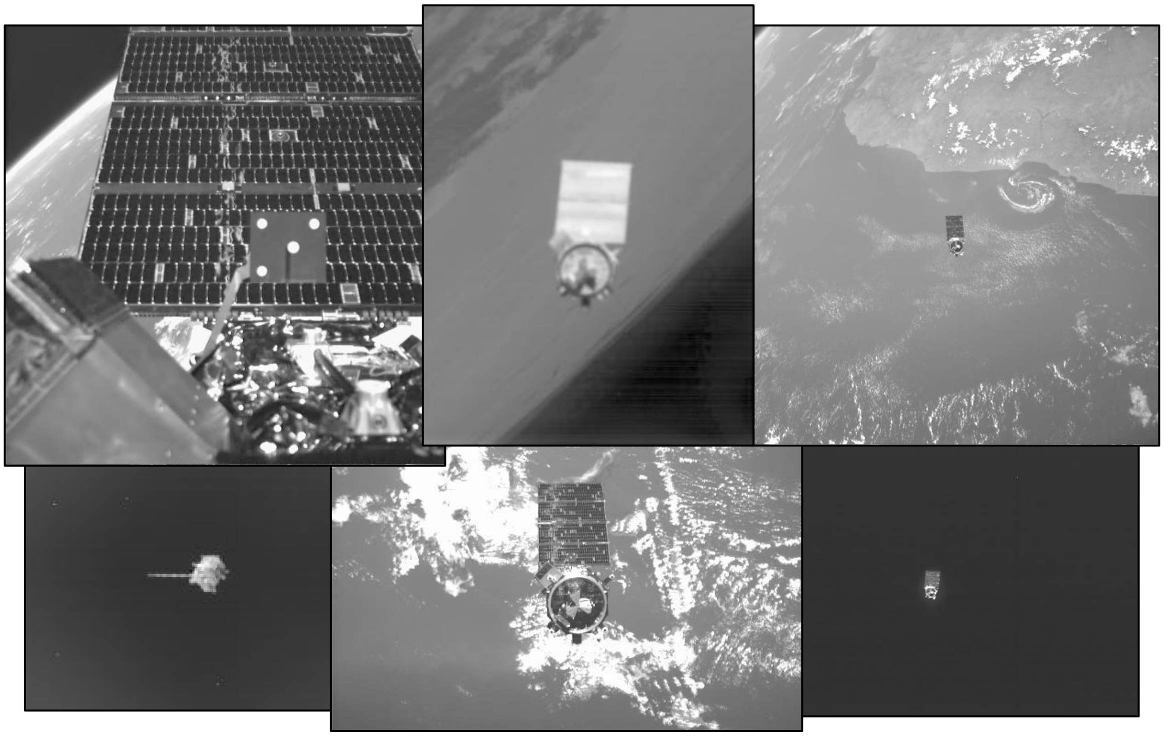

Figure 23.– Exercise #4 Photos

AR&C EXERCISE #5 (SCENARIO 8-2): 27-29 JUNE 2007 (UTC)

Exercise #5 Plan

AR&C exercise #5 intended to stretch sensor tracking to new limits, using Vis-STAR software updated after exercise #2, and input parameters for both Vis-STAR and AutoNav adjusted after exercise #4. The guidance sequence intentionally interrupted the 741 trajectory to stop at 4 km and test one round of standoff mode. Standoff executes a racetrack-shaped trajectory intended to spend long periods of time with low propellant expenditure. The sequence would then proceed to 120 m, wait for good lighting, and execute a 100 m radius near-circular flyaround inspection – this time at three times orbital rate. ASTRO would then fly its way to the approach corridor and do a solar inertial approach, followed by a second attempt at autonomous grapple and berth.

- Maximum range = 7 km
- Unmated $1^{d}\ 1^{h}\ 25^{m}\ 45^{s}$ within $\pm 5^{m}$
    - Nighttime demate with sun β = 44.0°
    - Solar inertial separation to 78 m above and slightly left of NextSat
    - Phasing to –7 km (behind NextSat)
    - Return to –4 km
    - Standoff mode for ~$6^{h}\ 44^{m}$
    - Proceed to –120 m V-bar stationkeep and await proper lighting
    - 100 m near-circular inspection flyaround at 3 times orbital rate
    - +120 m V-bar stationkeep
    - Transfer to 60 m corridor
    - Solar inertial approach

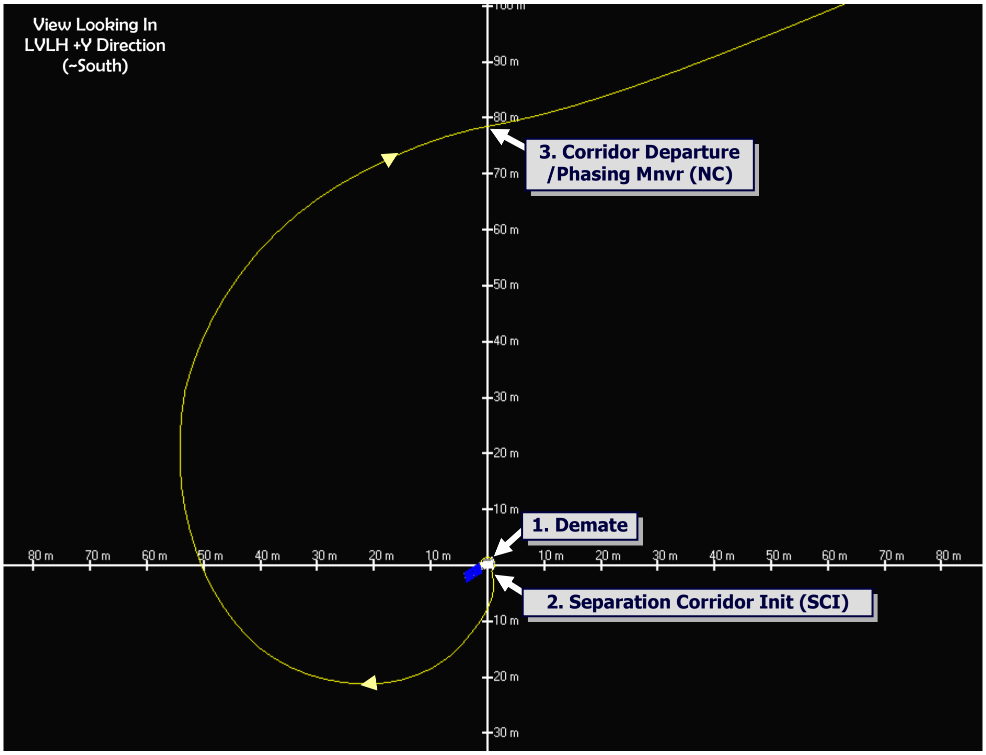

Figure 24.– Exercise #5 Planned In-Plane Corridor Separation Trajectory
(Simulated with BSTAMPS/SimWorks)

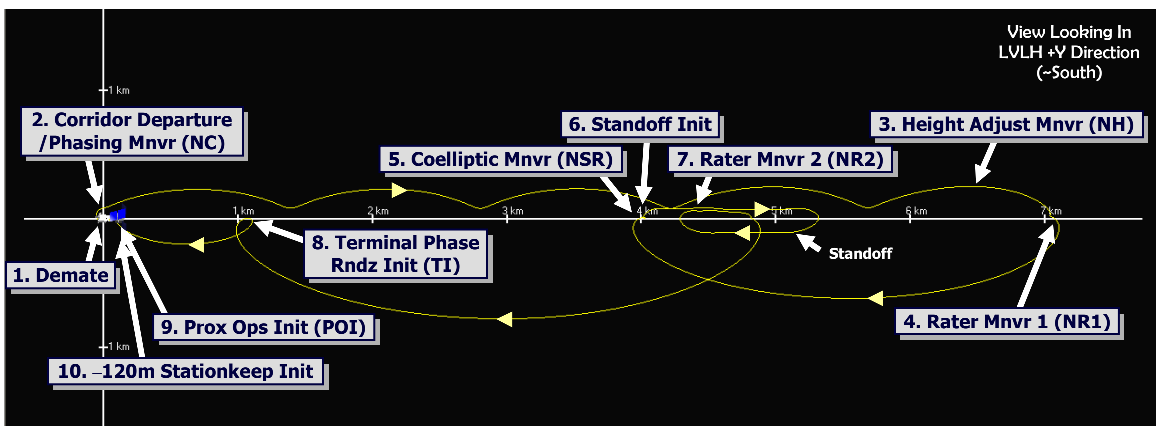

Figure 25.– Exercise #5 Planned In-Plane Rendezvous Trajectory
(Simulated with BSTAMPS/SimWorks)

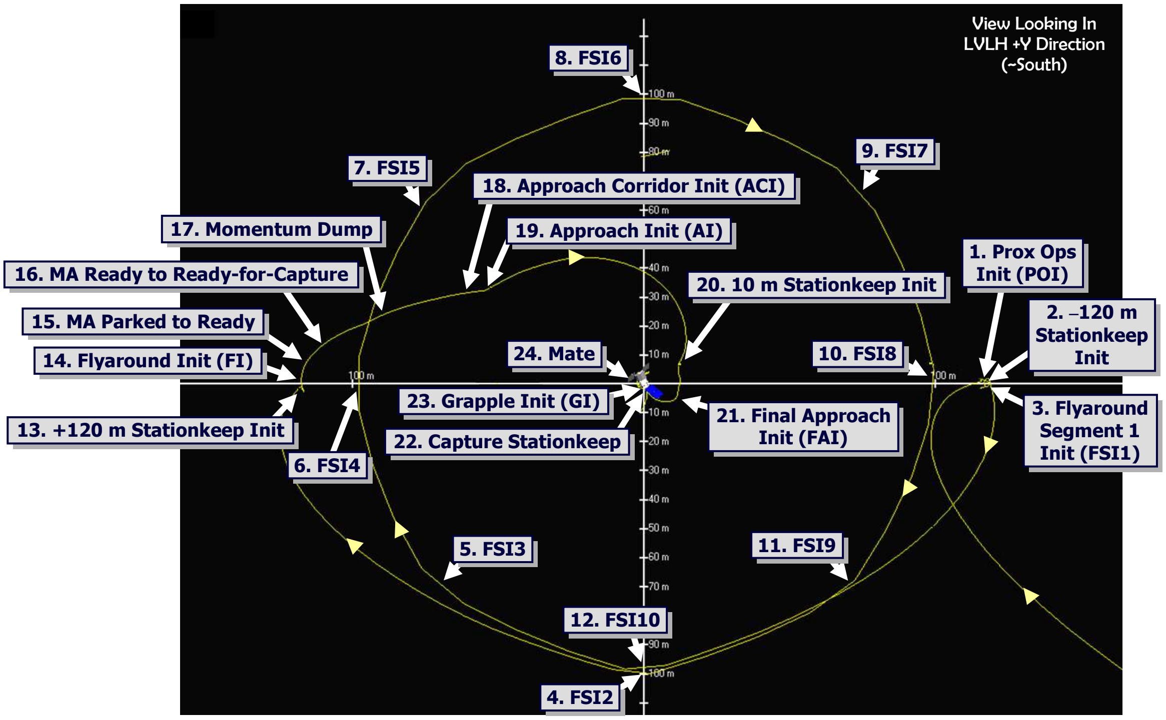

Figure 26.– Exercise #5 Planned In-Plane Proximity Operations Trajectory
(Simulated with BSTAMPS/SimWorks)

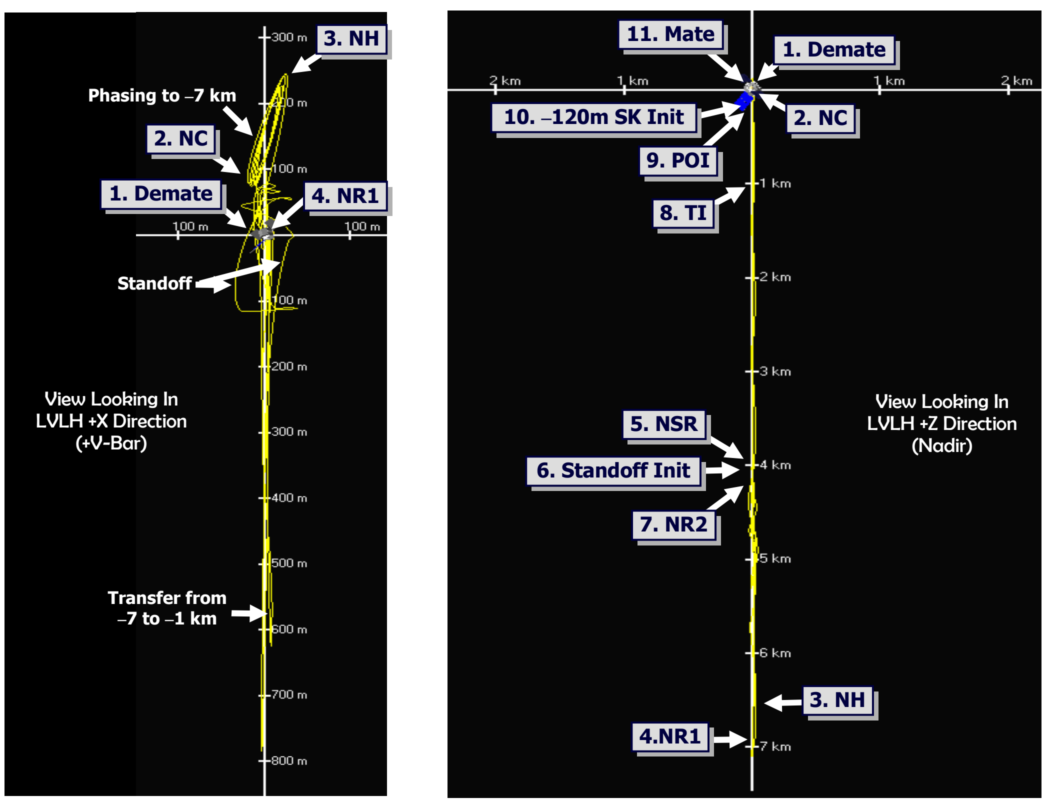

Figure 27.– Exercise #5 Planned Out-of-Plane Relative Trajectory
(Simulated with BSTAMPS/SimWorks)

Exercise #5 Results

The trip to –7 km and back proceeded smoothly. The only issue was with rejection by AutoNav of good LRF returns at long ranges. Fortunately, Vis-STAR data, fed by camera images, provided a sufficient NextSat navigation state. This, combined with a forgiving trajectory and continuous targeting, permitted ASTRO to exit the standoff mode and proceed with the nominal rendezvous. As ASTRO approached –120 m, LRF returns combined with Vis-STAR extended target tracking, provided excellent range measurements.

The flyaround also followed the plan, as NextSat was illuminated and the sun stayed outside the ASTRO camera fields-of-view. ASTRO proceeded to the approach corridor and added AVGS to the tracking suite, making relative navigation very robust during approach to the capture stationkeep box. Exercise #5 fuel usage was less than simulated.

The ground team observed NextSat during grapple, using real-time downlinked video as ASTRO/NextSat passed over HULA within the 10 minute designated window. As the team watched, NextSat unexpectedly moved out of the camera field-of-view. For a few minutes, the ground was uncertain whether NextSat was within ASTRO's grip, or if a missed grapple had occurred, in which case the ground was prepared to back ASTRO away from NextSat. The arm operator finally concluded NextSat was grappled. Further analysis concluded the arm end effector assumes some internal friction exists as the grapple fixture enters with a bit of misalignment. This friction contributes to an internal mousetrap being tripped, which then stops the end effector from driving forward. During this grapple activity, the end effector was perfectly aligned and kept driving forward until a soft-stop was reached in the arm joints. This left NextSat in an awkward, offset position, but with no harm done to it. The ground proceeded with manually berthing NextSat to ASTRO.

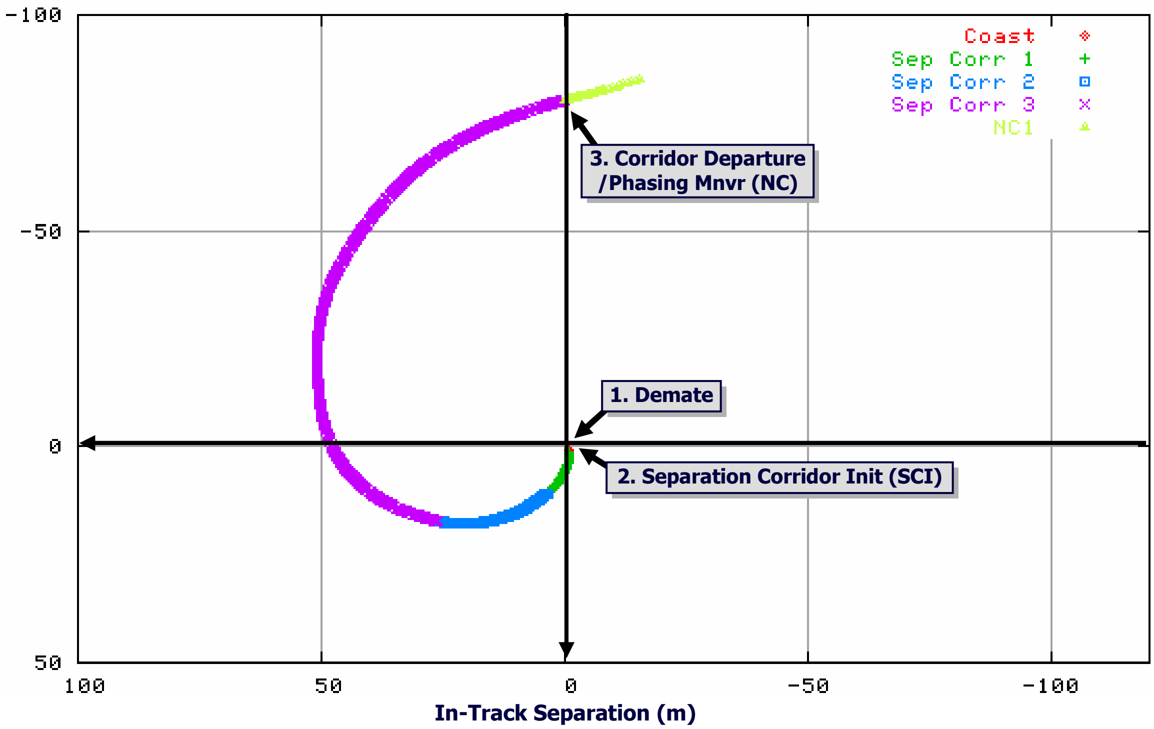

Figure 28.– Exercise #5 Actual/Onboard In-Plane Corridor Separation Trajectory

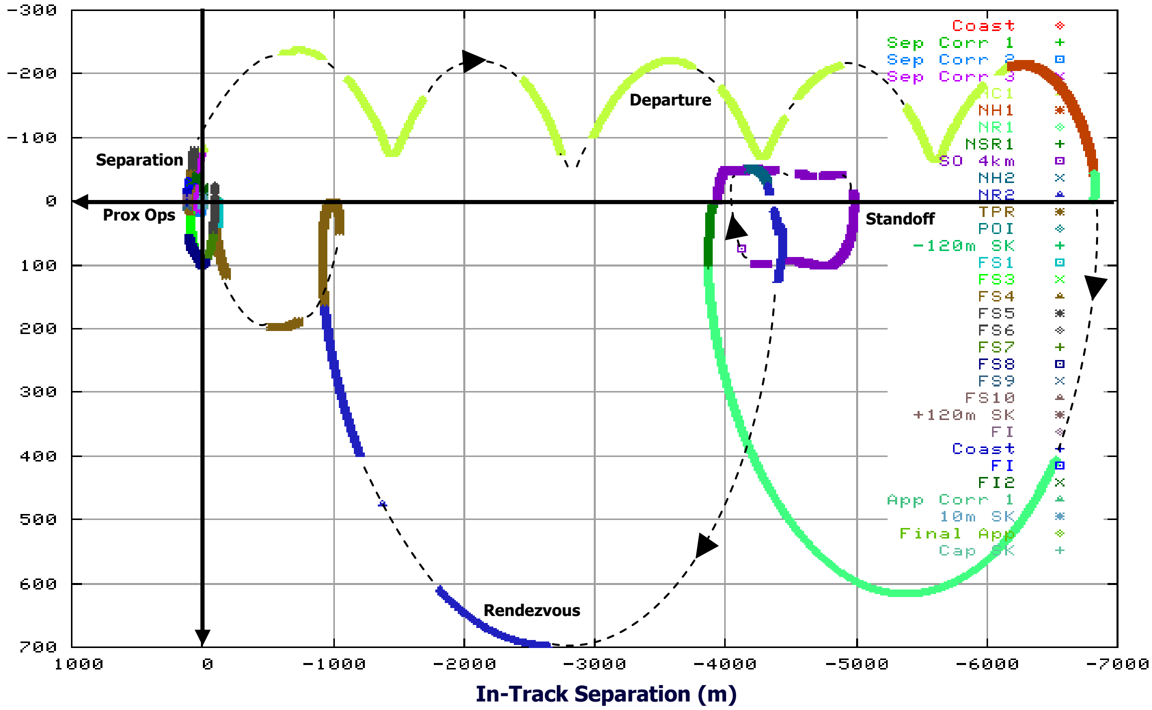

Figure 29.– Exercise #5 Actual/Onboard In-Plane Rendezvous Trajectory

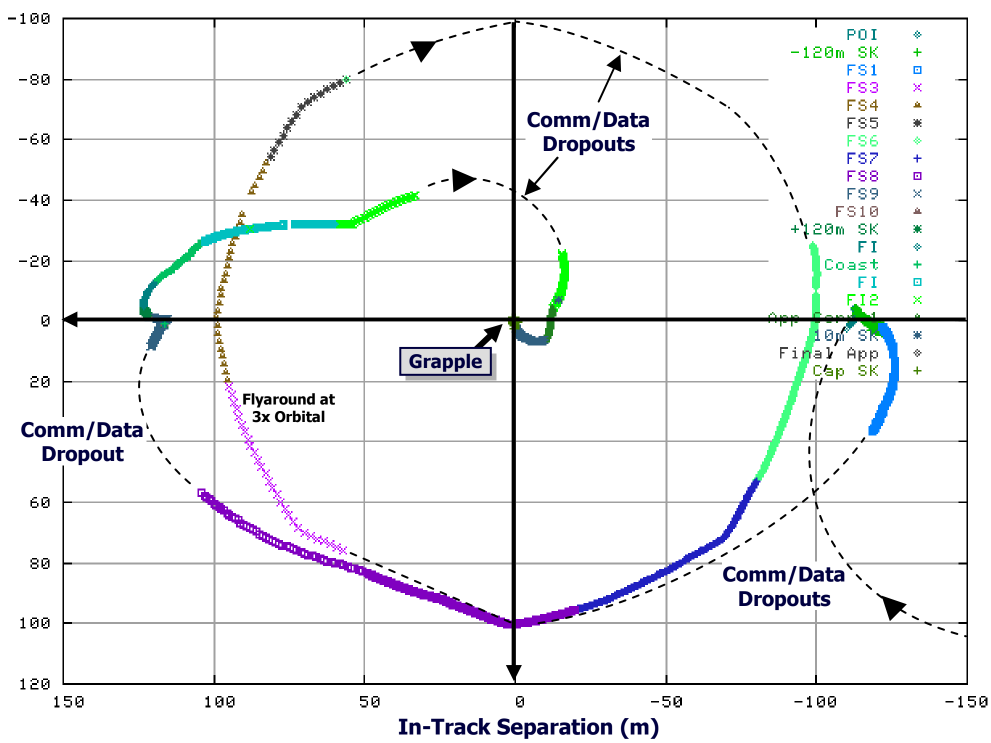

Figure 30.– Exercise #5 Actual/Onboard In-Plane Proximity Operations Trajectory

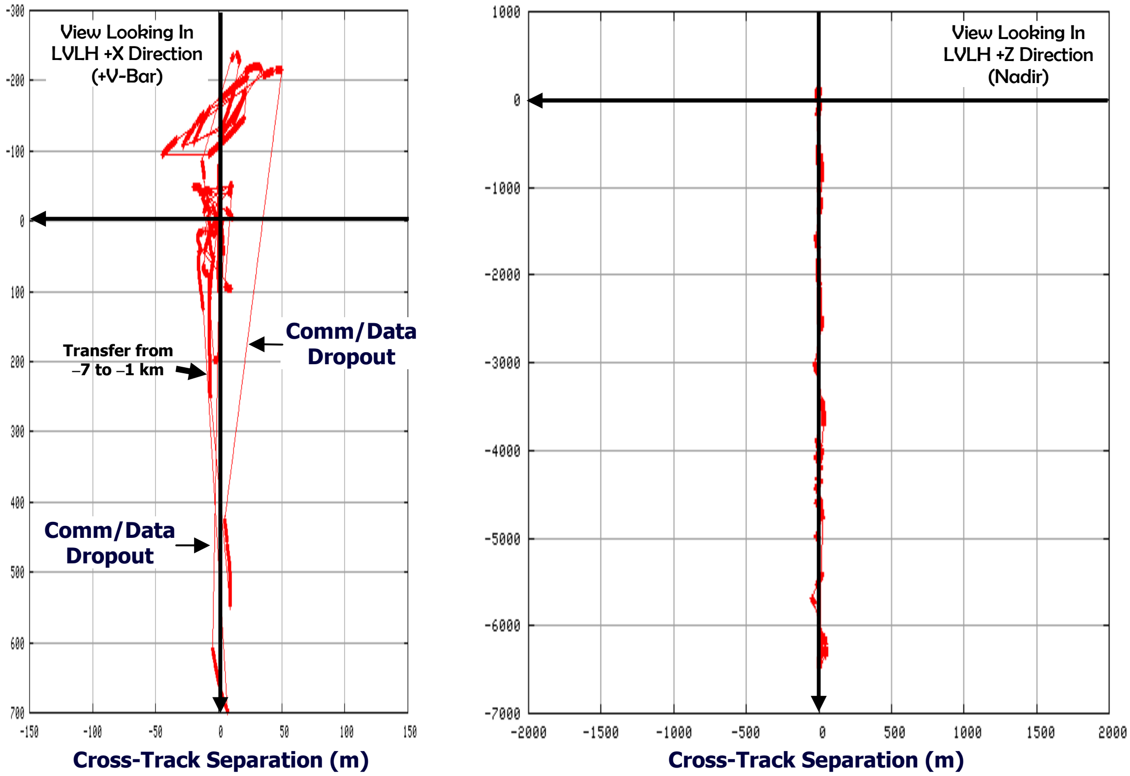

Figure 31.– Exercise #5 Actual/Onboard Out-of-Plane Trajectory

Exercise #5 Summary

- Maximum range = 7 km
- Unmated for $1^{d}\ 21^{h}\ 54^{m}\ 19^{s}$
  - Demate (UTC): 27 June at $8^{h}\ 9^{m}\ 13^{s}$
  - Grapple initiation: 28 June at $9^{h}\ 31^{m}\ 55^{s}$
  - Mate: 29 June at $6^{h}\ 3^{m}\ 32^{s}$
- Propellant use = 3.8 kg
  - Pre-exercise estimate = 4.0 kg

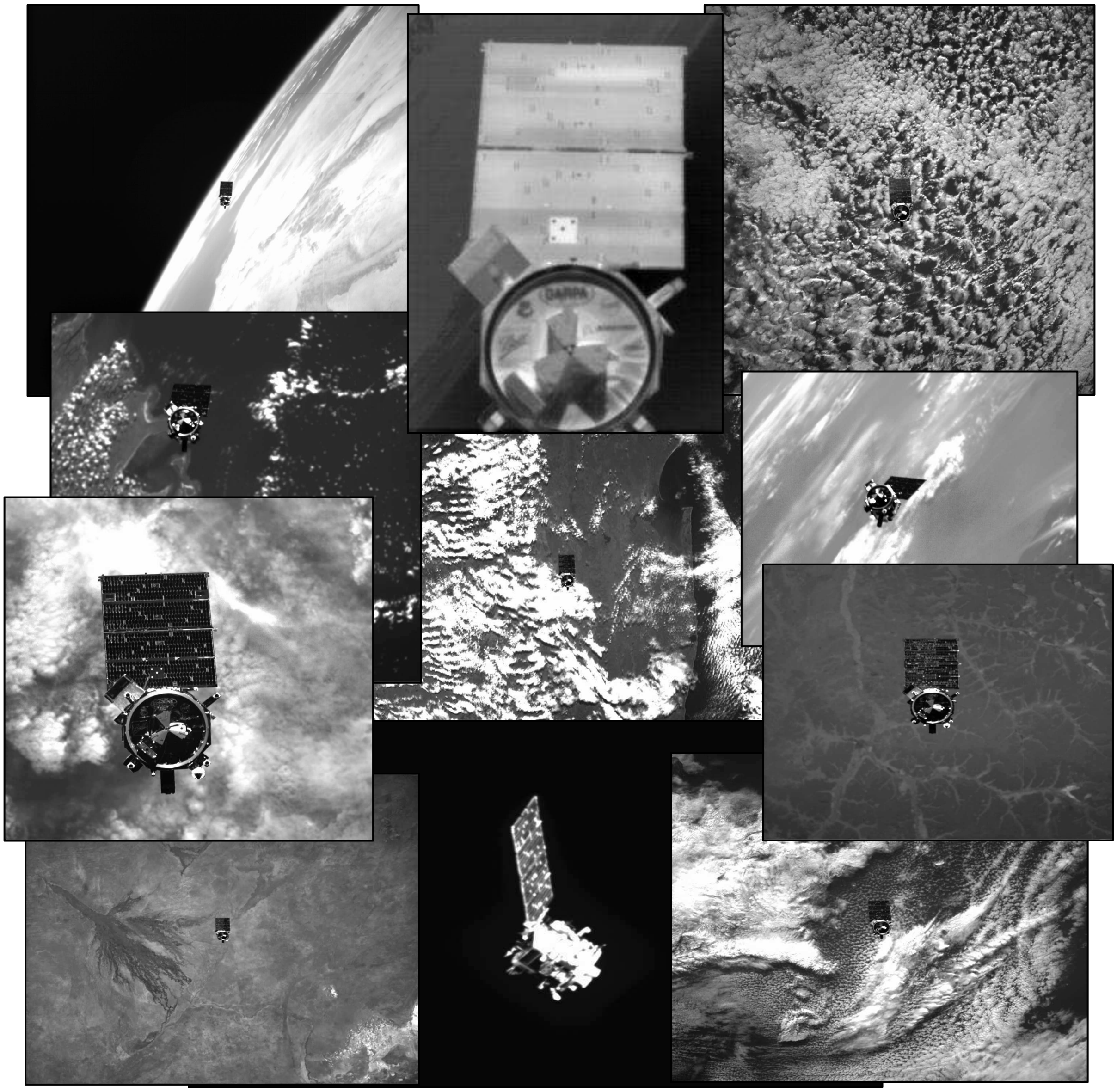

Figure 32.– Exercise #5 Photos

AR&C END-OF-LIFE EXERCISE: 17-20 JULY 2007 (UTC)

End-of-Life Exercise Plan

The primary EOL objective was to leave both spacecraft in safe, harmless states in which they would not re-contact each other, and would deorbit naturally within 25 years. Simulations showed that given ASTRO's higher ballistic number, it could be raised above NextSat and meet these conditions. A trajectory was built to raise ASTRO 15 km above NextSat and enter an out-of-plane corkscrew trajectory using a pair of EXDV burns. The corkscrew would decrease probability of re-contact, while permitting the opportunity to test this contingency mode not needed during the mission. To kick things off, the initial corridor separation was extended an extra orbit to keep ASTRO aligned with NextSat longer and further the range to which AVGS would track NextSat.

Given two healthy spacecraft and a 90% full propellant tank, DARPA added objectives to be accomplished prior to before raising the ASTRO altitude. DARPA directed Boeing to fly ASTRO behind NextSat until beyond sensor range, load a new NextSat state vector gathered from ground tracking, and execute autonomous rendezvous to a standoff condition between –500 m and –1 km. From there, ASTRO would ascend to 15 km above NextSat. Sensors would track NextSat to a maximum range, and upon reaching –1000 km, the exercise would be complete.

- Maximum range = 1000 km
- Unmated duration to –1000 km outbound: unspecified
- Part 1: Demate to –300 km and return to –500 m standoff
  - Nighttime demate over COOK with sun β = 26°
  - Solar inertial separation to 150 m above NextSat
  - Stairstep phasing to –300 km (behind NextSat)
  - Descend to 7 km below NextSat
  - Close on NextSat in a coelliptic orbit
  - Intercept V-bar at –7, –4, and –1 km
  - Standoff init β = 20°
  - Standoff between –500 m and –1 km, by alternating between 30 m above and below V-bar
  - Real-time decision to rename onboard data loads and proceed with Part 2
- Part 2: Move ASTRO to a safe orbit above NextSat
  - Posigrade height adjust and coelliptic burns to 15 km above NextSat
  - 2 EXDV burns resulting in safe out-of-plane corkscrew trajectory
  - Coast to –1000 km (beyond sensor range)
  - End in sun track attitude
  - Upon reaching –1000 km, NextSat, then ASTRO, would be decommissioned by emptying propellant, rotating one ASTRO solar panel 180° from the other and delivering "poison pills" to the onboard computers so the spacecraft could not be reactivated.

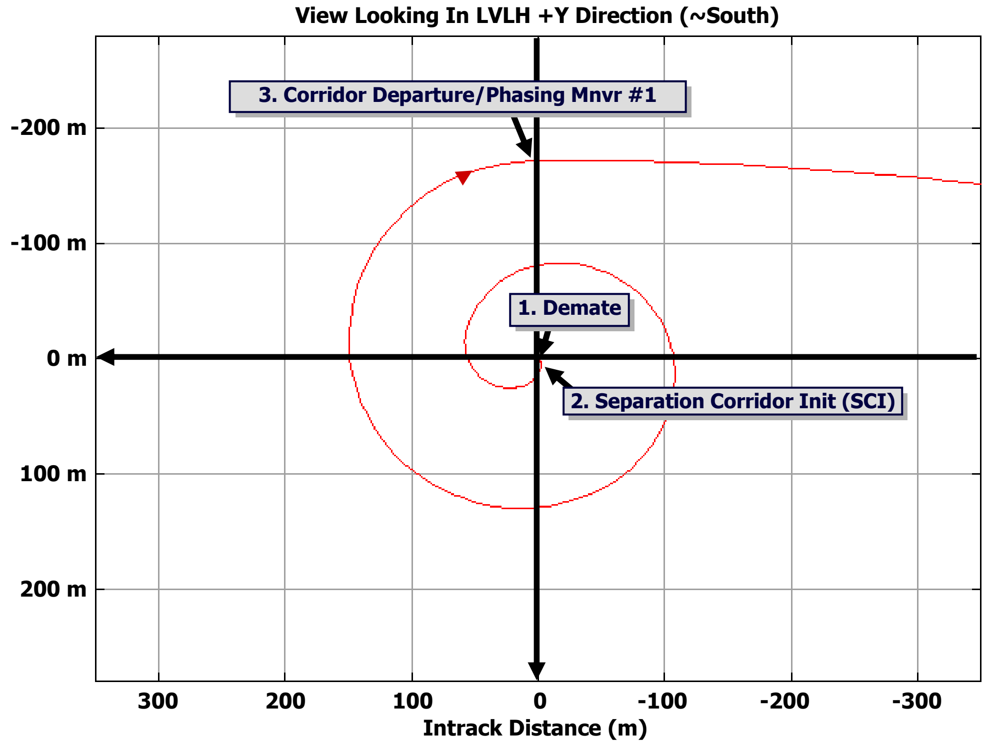

Figure 33.– End-of-Life Exercise Planned In-Plane Corridor Separation Trajectory (Simulated with BSTAMPS/SimWorks)

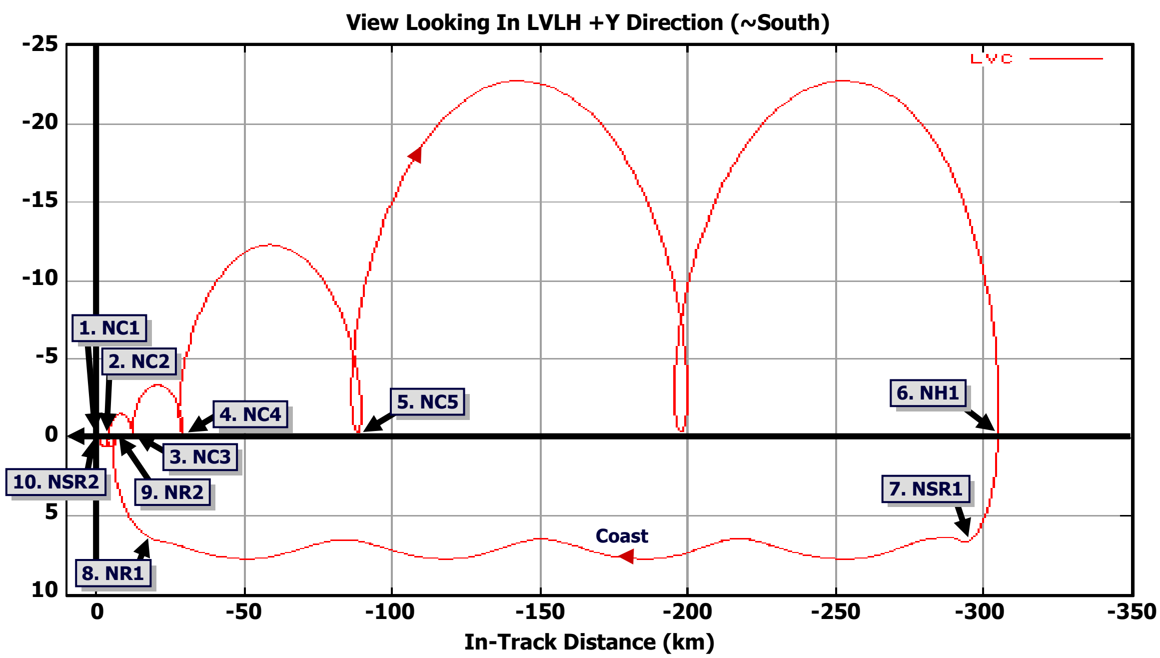

Figure 34.– End-of-Life Exercise Planned In-Plane Outbound and Rendezvous Trajectory (Simulated with BSTAMPS/SimWorks)

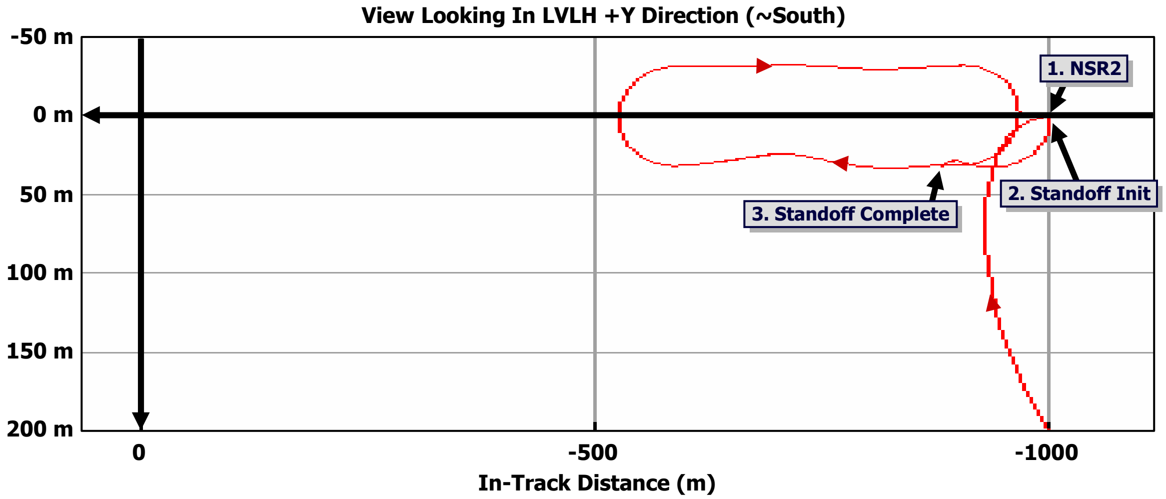

Figure 35.– End-of-Life Exercise Planned In-Plane Standoff Trajectory
(Simulated with BSTAMPS/SimWorks)

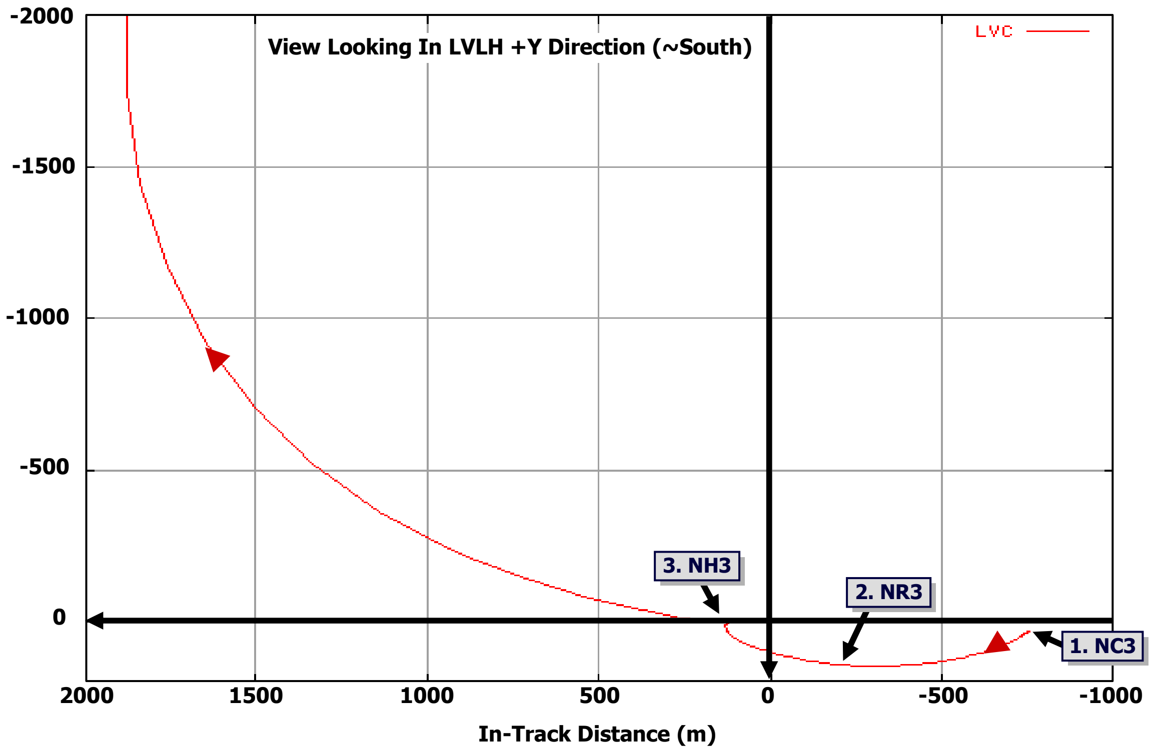

Figure 36.– End-of-Life Exercise Planned In-Plane Transfer and Early Departure
(Simulated with BSTAMPS/SimWorks)

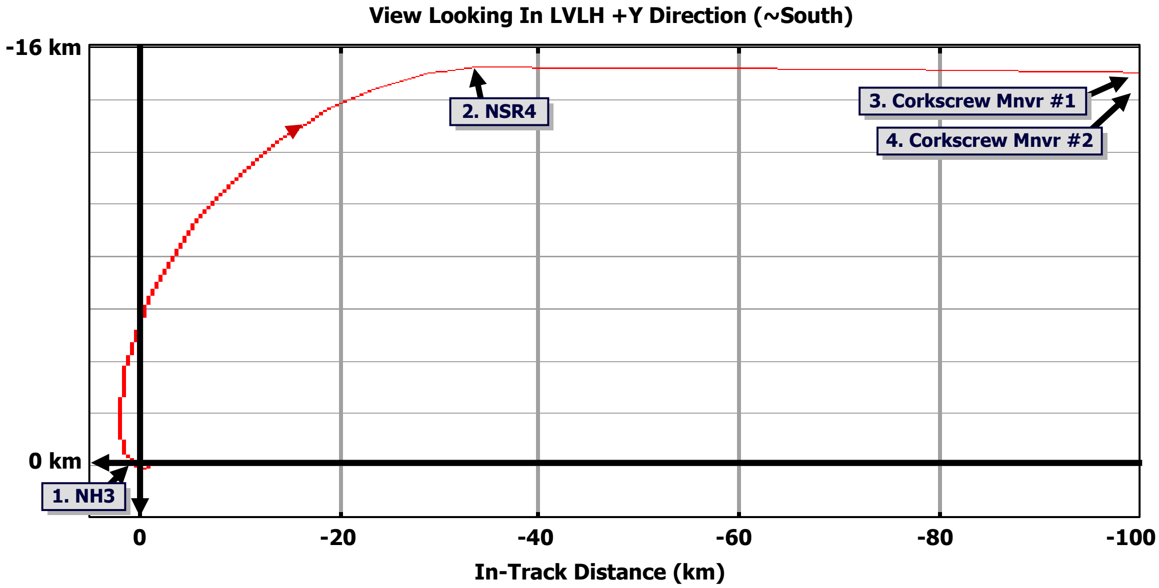

Figure 37.– End-of-Life Exercise Planned In-Plane Departure to 15 km Above NextSat (Simulated with BSTAMPS/SimWorks)

End-of-Life Exercise Results

Subsystems performed very well during their final days. During outbound phasing, the NFOV visible camera tracked beyond the 200 km required of it, so a last-minute real-time decision was made to postpone the onboard-commanded burn that would have started a return from 300 km. Instead, ASTRO was ground-commanded to continue coasting while the ground monitored camera track performance. There was no evidence of camera tracking during the scant communications available during the following orbit, so the decision was made to return at the end of the orbit – approximately 410 km behind NextSat.

ASTRO dropped to a co-elliptic orbit 7 km below NextSat's orbit and closed from behind. The ground replaced the onboard NextSat state vector with one based on ground tracking. When good lighting occurred at 380 km, the NFOV camera picked up NextSat and AutoNav incorporated data. This repeated itself when NextSat was front-lit each orbit.

Given the lack of elevation variance that exists with a co-elliptic orbit, relative navigation was good enough from camera tracking to proceed with the Rater-targeted burn targeting –7 km on the V-bar, but it wasn't great. ASTRO executed the 741 stable orbit rendezvous built for this mission and designed for operational LEO rendezvous missions. Between the elevation angle variance, newly-received LRF data, and continuous targeting, the trajectory improved.

Upon arrival at 1 km, guidance entered a standoff ("racetrack") mode 30 m above and below the NextSat V-bar. As relative navigation continued to improve, it was concluded ASTRO was less than 30 m below the V-bar and closing slower than expected. This was not a problem, and, in fact, reduced propellant use. AutoNav continued to accept highly-accurate LRF range measurements on the first leg of the racetrack, when the LRF appeared to fail. The mission operations team executed LRF recovery procedures, but was unsuccessful. The ground monitored navigation performance during the remainder of standoff and found angles-only tracking to be sufficient between 500 m and 1 km. An important contributor to this was the out-of-plane component inherent in standoff, which did not force ASTRO to be in-plane with the NextSat orbit.

After four laps around the racetrack and having been in standoff mode for $1^d\ 5^h\ 44^m$, DARPA directed Boeing to fly ASTRO to a point 500 m in front of NextSat. The ground uploaded a new set of instructions and ASTRO complied. After reaching 500 m, the second (and final) erroneous burn occurred. This burn pushed ASTRO behind NextSat with an opening rate. It was concluded that a proper fix would require a small GN&C code change. Given the fact ASTRO was on a mission to end its life, DARPA decided to close out the exercise. ASTRO was commanded to 15 km above, enter corkscrew, and coast to –1000 km behind and beyond. During coast, ground confirmed NFOV camera tracking and AutoNav incorporating measurements to a range of 506 km, and probably beyond, as communication with ASTRO was limited.

End-of-Life Exercise Summary

Prior to the EOL exercise, ASTRO carried 127 kg of its original 144 kg usable propellant (88%). After the exercise, but prior to decommissioning, ASTRO had 98 kg (68%). During decommissioning, all remaining propellant was burned or vented overboard.

- Maximum range = 1000 km
- Unmated duration to –1000 km outbound: $3^{d}\ 4^{h}\ 26^{m}\ 0^{s}$
  - Demate (UTC): 17 July at $3^{h}\ 41^{m}\ 0^{s}$
  - –1000 km outbound: 20 July at $8^{h}\ 7^{m}\ 0^{s}$
  - Propellant use = 29 kg

End-of-Mission

ASTRO and NextSat completed decommissioning and the mission concluded on 22 July 2007. The propellant depletion activity raised ASTRO's orbit to approximately 32 km above NextSat.

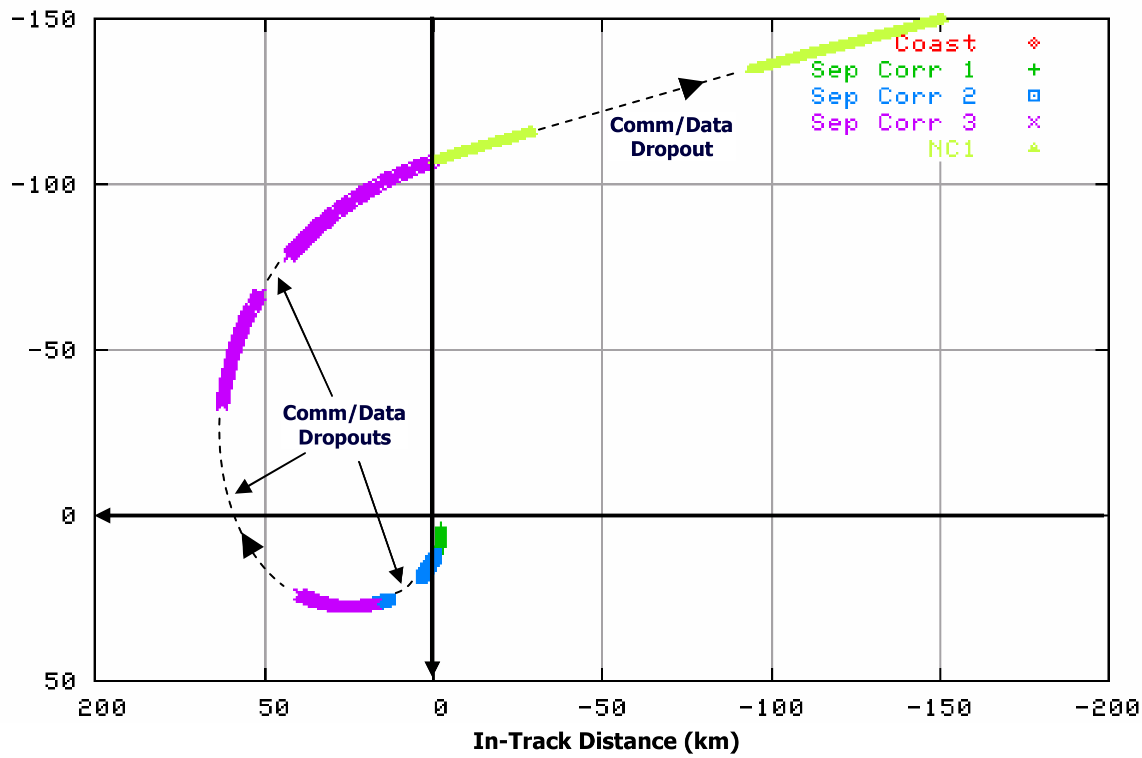

Figure 38.– Actual/Onboard In-Plane Corridor Separation Trajectory

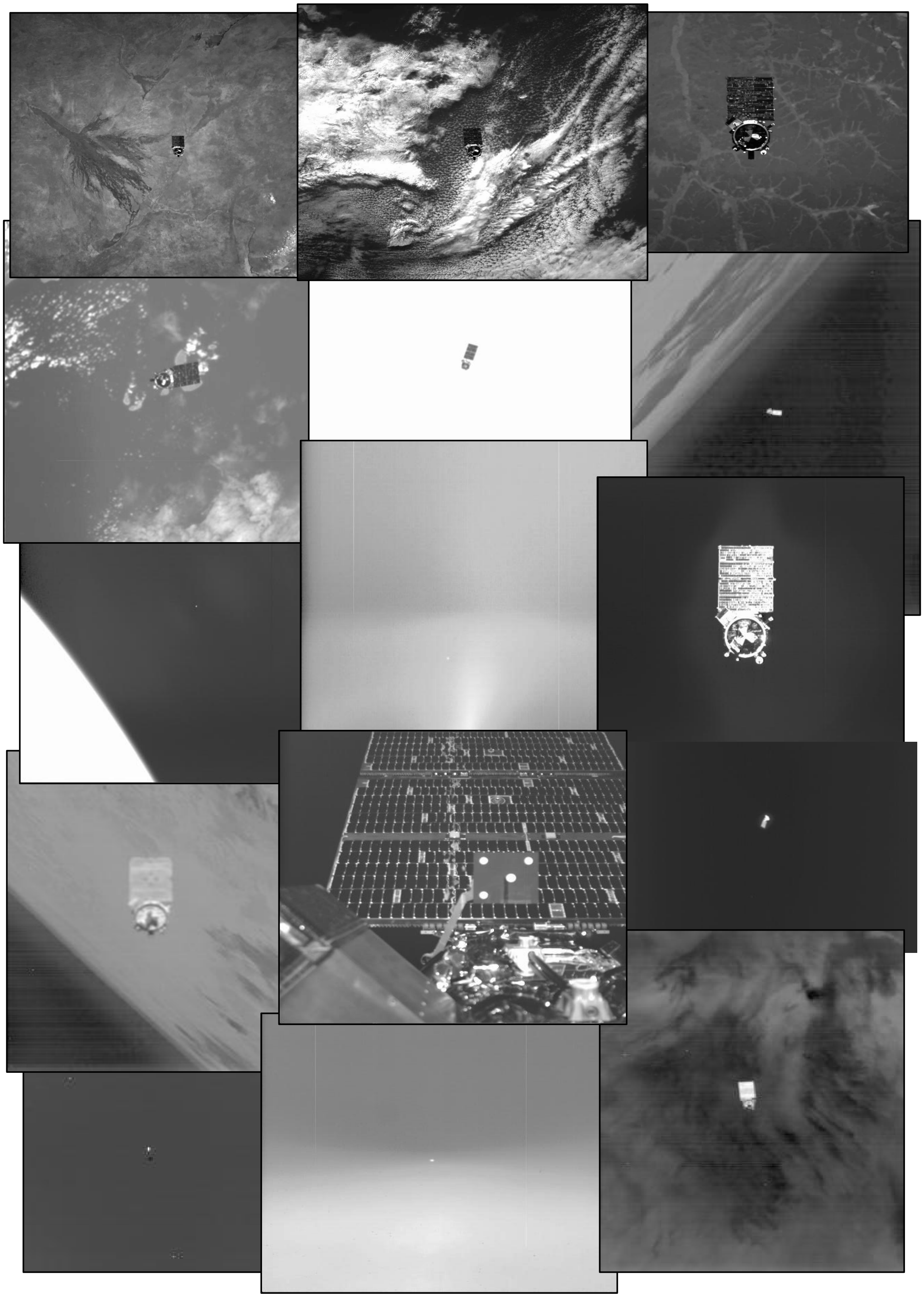

Figure 39.– End-of-Life Exercise Photos

ACRONYMS AND ABBREVIATIONS

AAS	**American Astronautical Society**
ACI	**Approach Corridor Initiation**
AFRL	**Air Force Research Laboratory**
AFSCN	**Air Force Space Communications Network**
AI	**Approach Initiation**
AIAA	**American Institute of Aeronautics and Astronautics**
AR&C	**Autonomous Rendezvous and Capture**
ASTRO	**Autonomous Space Transport Robotic Operations**
AutoNav	**Autonomous Navigation**
AVGS	**Advanced Video Guidance Sensor**
β	**Beta Angle**
BSTAMPS	**Boeing Spacecraft Trajectory Analysis and Mission Planning Simulation**
d	**Days**
DARPA	**Defense Advanced Research Project Agency**
EOL	**End-of-Life**
ESR	**Engineering Support Room**
EXDV	**External Delta Velocity**
FAI	**Final Approach Initiation**
FI	**Flyaround Initiation**
FSI	**Flyaround Segment Initiation**
FTAPS	**Fluid Transfer and Propulsion Subsystem**
GN&C	**Guidance, Navigation, and Control**
GPS	**Global Positioning System**
h	**Hours**
IEEE	**Institute of Electrical and Electronics Engineers**
Init	**Initiation**
INS	**Inertial Navigation System**
IRCam	**Infrared Camera**
km	**kilometer**
LIDAR	**Light Intensification Detection and Ranging**
LRF	**Laser Range-Finder**
LVLH	**Local Vertical Local Horizontal**
LVC	**Local Vertical Curvilinear**
m	**Meters *or* Minutes**
MSFC	**Marshall Space Flight Center**
NASA	**National Aeronautics and Space Administration**
Nav	**Navigation**
NC	**Correction Maneuver (Phasing)**
NCC	**Corrective Combination Maneuver (Lambert)**
NextSat	**Next Generation Serviceable Satellite**
NFOV	**Narrow Field-of-View**
NH	**Height Adjust Maneuver**
NR	**Rater Maneuver**
NSR	**Slow Rate Maneuver (Co-Elliptic)**
OE	**Orbital Express**
POI	**Proximity Operation Initiation**
Prox Ops	**Proximity Operations**
R-Bar	**Radial Vector**
Rel	**Relative**
RSC	**Research, Development, Test, and Evaluation Support Center**

RSR	**Rendezvous Support Room**
s	**Seconds**
SCI	**Separation Corridor Initiation**
SIGI	**Space Integrated GPS/INS**
Sim	**Simulation**
SK	**Stationkeep**
STP-1	**Space Test Program 1**
TDRS	**Tracking and Data Relay Satellite**
TI	**Terminal Phase Rendezvous Initiation**
UTC	**Universal Time Coordinated**
V-Bar	**Velocity Vector**
VisCam	**Visible Camera**
Vis-STAR	**Vision-based Software for Track, Attitude, and Ranging**
WFOV	**Wide Field-of-View**

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